[Abdruck aus den Astr. Nachr. Bd. 146.]

The First Satellite of Jupiter.

By *A. E. Douglass.*

[With a plate].

Observations upon this satellite were made in Mexico from February 18 to March 28, in the Clark 24 inch refractor of this Observatory, and in Flagstaff from May 16 to June 9, 1897. On April 4 and 18 the Grubb 15 inch refractor of the Mexican National Observatory was used. Definite markings on the first, third and fourth satellites were seen on February 18, 20 and 24 respectively; but those on the third and fourth were more easily followed and were constantly watched. Except some preliminary and routine micrometer measures of diameters, work on the first satellite was largely incidental, but in view of the approaching opposition of Jupiter it is desirable to reduce it to a form suitable for future use.

The results of the observations for detail on the third satellite have been published but much material has been gathered since then, including many old drawings made before the present work was begun. Reduction of the work on the fourth satellite was commenced, but met this curious obstacle, that either this satellite revolves in one-half of its period about Jupiter or the detail is symmetrical with respect to its axis. From the motion exhibited from day to day by the more conspicuous points of its detail the latter is judged to be the case. This result is especially mentioned because, from the recently completed reduction of observations on the first satellite, it is probable that its detail is also symmetrical with respect to its axis.

Upon three nights, February 28, March 5 and 6 movement of detail upon the first satellite was followed for about two hours; it moved toward terrestrial west, indicating a direct rotation. The seeing was good on these dates and on each occasion confidence was expressed in the direct rotation thus found. On March 7 some very characteristic detail was visible but the seeing was baffling and it could not be so well located. There seemed, however, a connection between two series of drawings separated by three hours, and a rapid direct rotation was indicated. On the 10th the satellite was followed for over two hours but no satisfactory result on this question was obtained, owing to the falling off in the seeing.

Professor W. H. Pickering, who first discovered the periodical change in form of this satellite, concluded from that study that its motion was retrograde. But his two series of measurements, one at Arequipa in December, 1892, and the other at Flagstaff in the autumn of 1894, were so separated that although the balance of evidence was in favor of the retrograde motion, it was not greatly so.

My own principal observations of movement of detail may be arranged in the following table, obtained by measurement on the original drawings.

The intervals used are from the first drawing to each successive one.

Febr. 28, E on map		March 5, A & B on map		March 6, I, J, K & L on map	
Time Int.	Motion	Time Int.	Motion	Time Int.	Motion
50^m	25°	19^m	2°	4^m	5°
59	25	51	16	42	19
69	18	87	30	70	32
87	28	—	—	95	40
114	50	—	—	—	—
120	35	—	—	—	—
132	45	—	—	—	—
156	50	—	—	—	—
787	276	157	48	211	96
Mean $0^\circ.35$ per minute		Mean $0^\circ.31$ per minute		Mean $0^\circ.45$ per minute	
21° per hour		18° per hour		27° per hour	

Assigning weights equal to the product of the total interval in minutes multiplied by the number of intervals, gives

Mean rate of rotation 22° per hour
Mean period 16.4 hours.

As the observations of markings were not continuous through great lengths of time, they were not sufficient to determine the map and rotation period by tracing the succession of detail, as on the third satellite, but they could, to a certain extent, confirm or deny any period otherwise found. So recourse was had to the observations of the changes in the elliptical form of the satellite, the same method used by Professor Pickering in his previous work.

The period found by him in 1892 was about 13^h, and so, to include any possible changes or errors, all periods from 12^h to 18^h were tested by plotting the measures of ellipticity on a series of glass slides such as those used at Harvard College Observatory for determining periods of variable stars. The amount of displacement of the slides, required to produce agreement between different measures, determines the period. The only periods in which the seventy-four measurements of ellipticity showed passable agreement were $12^h 25^m.8$, $13^h 40^m.6$, $15^h 18^m.5$ and about $17^h.1$. The last named was at once discarded because it showed distinctly more discordance than the other three. The periods $12^h 25^m.8$; $13^h 3^m 25^s.8$; $13^h 3^m 9^s.3$ (Professor Pickering's direct and retrograde periods, respectively); $13^h 20^m.0$ (suggested by a preliminary inspection of detail); $13^h 40^m.6$; $15^h 18^m.5$ and others, were then applied rigorously to the observations by, separately for each period, determining the longitude of the center of the satellite for each observation and plotting the ellipticity for the longitudes obtained. The use of a calculating machine saved much labor in these trials.

The resulting curves showed at once that the only periods to be considered were $12^h 25^m.8$ and $15^h 18^m.5$, and of these the former was the preferable. In assigning central longitudes to each observation that at the first observation on March 4 at $19^h 42^m$ Gr. M. T. was in each case called 341° in order to have a certain reference to the map based on the period $12^h 25^m.8$. The ellipticities were, throughout, given by a single number which represented the equatorial diameter, when the polar diameter was exactly 100. With this explanation I can describe the curve given by the period $15^h 18^m.5$ as having two well marked maxima, one of 128 (ellipticity) at central longitude 110° and the other of 123 at longitude 296°. The first of these is preceded by two closely adjacent minima of 116 at 70° and 96°, separated by a rise in the curve nearly to 120. The second maximum is also closely preceded by a minimum of 114 at 270°. It will be seen that while the maxima are closely two quadrants apart and the minima are the same, the curve from minimum to minimum is not symmetrical but leaps at once from minimum to maximum and then slowly descends. The most regular curve which can be applied to it has minima of 114 at 87° and 267° and maxima of 126 at 117° and 297° and nearly straight slopes between these points. But even from this line the observations show larger variations than from the symmetrical curve applied to the period $12^h 25^m.8$.

The curve obtained from the period $12^h 25^m.8$ has minima of 116 at 150° and 114 at 320°. There is a slight tendency for the ascent after the minima to be steeper than the descent immediately preceding them, and the first maximum is more pronounced, that is, higher, than the second, but that is probably due to the scarcity of observations in that vicinity. On the whole there seems to be no need for assigning a non-symmetrical curve. The best one to fit this period has well-defined minima of 115 at 141° and 321° and very indefinite maxima of 125 near longitudes 51° and 231°. The curve does not drop to 124 until 50° distant from the maxima. The average residual from this curve is only a little over two one-hundredths of the polar diameter. From the special curve of the other period it is about three one-hundredths.

There is another criterion which decides in favor of the period $12^h 25^m.8$, namely, the observations of detail. There are ninety-one of these drawings, including two by Dr. T. J. J. See, made on thirty-one different nights. To facilitate the study of them, certain combination drawings were made and the number reduced to seventy-two. In order to compare these, charts were made on sheets of paper ruled vertically, by placing each separate drawing in the position of its own longitude; sketches then, of the same longitude formed vertical columns down the page. By this means the following periods were tried: $5^d 0^h.0$ suggested by a preliminary inspection of detail; $42^h.47$, its period about Jupiter; $40^h.0$, or one-third of the 5 day period; $15^h 18^m.5$; $13^h 37^m.4$, by mistake for $13^h 40^m.6$ but not materially differing from it; $13^h 20^m.0$, one-ninth of the 5 day period; $12^h 37^m.9$, intermediate in hourly rate of surface between 12^h and $13^h 20^m$; $12^h 25^m.8$.

Of these periods $15^h 18^m.5$ was one the least satisfactory and its fairly successful application to the ellipticities must be considered accidental; $13^h 20^m.0$ showed some striking isolated agreements of detail; but for the entire series of drawings $12^h 25^m.8$ was better than any other and was therefore adopted as the period of the first satellite during the spring of 1897.

Having thus found the period from investigation of ellipticities and detail, a longitude was assigned to each original drawing and each one then copied upon a small graduated wooden ball properly adjusted. There was surprisingly little discordance between drawings; almost every one was found to adapt itself readily to the others on the globe. The most conspicuous marking was the one first seen on February 18 and consisted in a broken north and south line, the center being slightly misplaced in a following direction. This is very similar to Professor Pickering's drawing in Astronomy and Astro-Physics, June, 1893 and is perhaps identical with it. In his line the north end is heavier, however, while in all my drawings the south half is more distinct.

From the angle formed at the center of this marking two lines were seen several times, passing, one in a north-following and the other in a south-following direction, as if the whole configuration consisted of two long lines crossing at this point. For convenience in reference the four branches taken in order, south-preceding, north-preceding, south-following and north-following are called, provisionally, A, B, C and D. Preceding this by nearly sixty degrees is another cross somewhat resembling it, and to its four branches the letters I, J, K and L have been given provisionally. The point midway between these two large markings has been chosen as the initial longitudes, for, by this means, the whole symmetry of the markings becomes more readily measured by the eye.

Following A, B, C and D there was, in some of the latest drawings, a suspicion of a vertical line at 60° longitude but it was extremely doubtful; it was donated by E′. Nothing certain was reached until E appeared as a north and south line at longitude 120°; then F at 160° and G at 210°, vertical lines with their south ends joined, and with a suspected line G′ extending from this juncture in the north-following direction; then H at 270°.

Upon measuring the positions of these lines in every drawing in which they appeared the following longitudes were obtained.

	A, B, C & D considered as one marking	E′	E	F	G	G′ about	H	I, J, K & L considered as one marking
Longitude	27°	65°	120°	164°	210°	220°	275°	333°
No. of times drawn	24	4	17	22	17	2	10	27
Average residuals	9°	8°	10°	10°	18°	—	8°	13°

In these measurements the identification of a line depended largely upon its location upon the disc.

The largest average residual is found in G because on March 10 several drawings persisted in showing it very close to F. The general average residual for a single observation of a marking was 11°.4 of longitude. That is very closely one-tenth of the diameter of the satellite.

The general distribution of marking can be best described, and their symmetry best illustrated, by saying that they nearly form portions of five great circles passing around the satellite. Two of these intersect to form A, B, C and D on one side and G on the other. Two more form I, J, K and L on one side and F on the other. These four circles are each inclined about 30° to the axis of the satellite. The joining of the upper half of F and G coincides with this location of these circles and G′ is near the one which passes through F. The upper half of F has at times been drawn broad as if it were also connected with E. The fifth circle is parallel to the axis and in its intersection with the equator is intermediate between the others. It passes almost through H on one side and is midway between the suspected E′ and E on the other.

Upon dividing the full series of observations into convenient periods of about eleven days each and determining for each period the mean position of the detail, it was found that no correction to the adopted period of $12^h 25^m.8$ would produce improvement.

The axis of the satellite is assumed to be perpendicular to the plane of its orbit in the above description of detail. Something of that kind is indicated by the movement of detail but the observations are too difficult to give anything decisive. Dr. Barnard reached that conclusion from observations on the bright equatorial regions (Monthly Notices Roy. Astr. Soc. Vol. LIV, No. 3, page 134). In this article he states that he was led to believe its period of rotation not the same as that around Jupiter.

Micrometer measurements give a very elliptical form to the first satellite. Each individual measurement used in computing the table below is the mean of six or more settings and except for two successive measurements of the equatorial diameters of the first satellite, only one measurement of a given dimension was made in an evening. For purposes of comparison the values for all four satellites are given, but the absolute results are only provisional, for the computation was not rigorous and the latest value of the micrometer constant has not been used and my personal irradiation constant has not been determined. The measures however are clustered about opposition-time when the distance of the planet was nearly constant, and, except for irradiation, they are probably very near the final values. The table is repeated below with the approximate values in miles.

(1)

	I		II		III		IV	
	Polar	Equat.	Polar	Equat.	Polar	Equat.	Polar	Equat.
Mean diameters	0".84	1".07	0".74	0".78	1".57	1".58	1".45	1".51
Number of measurements	11	11	10	10	9	9	10	9
Average residuals	0".08	0".06	0".05	0".03	0".04	0".07	0".09	0".08
And one obs. with satellite on Jupiter	0".67	0".93	—	—	—	—	—	—
Reducing radii by	0".08	0".07	—	—	—	—	—	—

For approximate values in miles, 1".0 = 1990.0 miles. Mean distance from the Earth = 4.42.

(2)

	I		II		III		IV	
	Polar	Equat.	Polar	Equat.	Polar	Equat.	Polar	Equat.
Mean diameters	1672	2129	1473	1552	3124	3144	2886	3005
Number of measurements	11	11	10	10	9	9	10	9
Average residuals	159	119	100	60	80	139	179	159
And one obs. with satellite on Jupiter	1333	1851	—	—	—	—	—	—
Reducing radii by	170	139	—	—	—	—	—	—

Polar and equatorial diameters mean respectively perpendicular and parallel to the belts of Jupiter. I can account for the smallness of these results only on the supposition that my unconscious correction for irradiation is very large.

This gives a mean value of 130 for the ellipticity of the first satellite. The mean value measured on the scale of ellipticities is closely 122 and the variations from it not nearly so great as in the micrometer measurements. With the micrometer the probable error of a single observation of relative diameters is nearly four times as great as by the scale of ellipticities and it is likely that irradiation has also a larger share in its results.

Below is given in detail a collection of observations which bear upon the ellipticity of this satellite and the causes of this peculiar form. The appearance of the satellite when in transit has an important bearing upon the theory that its apparent form is due to detail. Upon March 3 I was measuring its polar diameter by the micrometer as it approached transit and the final setting was made when it was half on the planet, but there was no effect upon the reading. One minute later the position angle of its elongation was taken with perfect confidence in the result, and after it had been on ten minutes a drawing of its detail was made, showing its full size. On the 22^d of February measures of its diameters were made while it was from 8^m to 16^m in transit. The individual settings were entirely concordant and there is no effect of changing diameters as it reached brighter portions of Jupiter, nor was there any visual suspicion that the ellipticity had altered; the satellite seemed to be of the usual elliptical form. The measures gave an ellipticity of 139. On March 10 it was observed 22^m after entering upon the disk of Jupiter; the polar zones had disappeared and only a long streak, three times as long as it was wide, could be discovered. During these observations it required $2^h 18^m$ to cross the equatorial regions of Jupiter and this last observation was therefore, on Jupiter, 43° from the apparent center.

From this series of observations we derive two points:

First, that, knowing the effect of irradiation to be inappreciable when the satellite is fairly on the Jovian disk, yet we find that both the visual observations and micrometer measures gave a marked ellipticity. In the diameters measured during transit the effect of removing irradiation was considerable. It amounted to 12 per cent of the average equatorial diameter while 9^m from the limb and 20 per cent of the average polar diameter while 14^m from the limb. The background was probably a little brighter during the latter measurement and therefore the change should be greater, but as no effect of brightening background appeared during consecutive settings for one or the other diameter, it should be very little greater. But if the equatorial regions were so much brighter that they caused the apparent ellipticity merely by irradiation, this change due to the absence of irradiation ought to be great on the equatorial diameter and almost inappreciable on the polar. That was not in the least the case.

Second, if it really was circular at that time the polar zones must have been very dark and defined with great sharpness, for the outline seemed perfect. One would expect such narrow black polar strips, a little later on, to show dark against the planet, but none did; they would be quite different from the general polar areas which disappeared.

If this ellipticity is due to surface markings, the markings must be of large size and very dark. If such a marking existed it would show itself at certain longitudes by some irregularities of the limb or by visibly projecting down into the disk. But the most conspicuous marking on the satellite apparently reaches up to a clean-cut and even limb and is so located that at one minimum phase it is 24° within the following equatorial limb and its heavy southern half is about the same distance within the southern limb. In other positions no distinct detail that has been seen could appreciably affect any part of the outline of the planet.

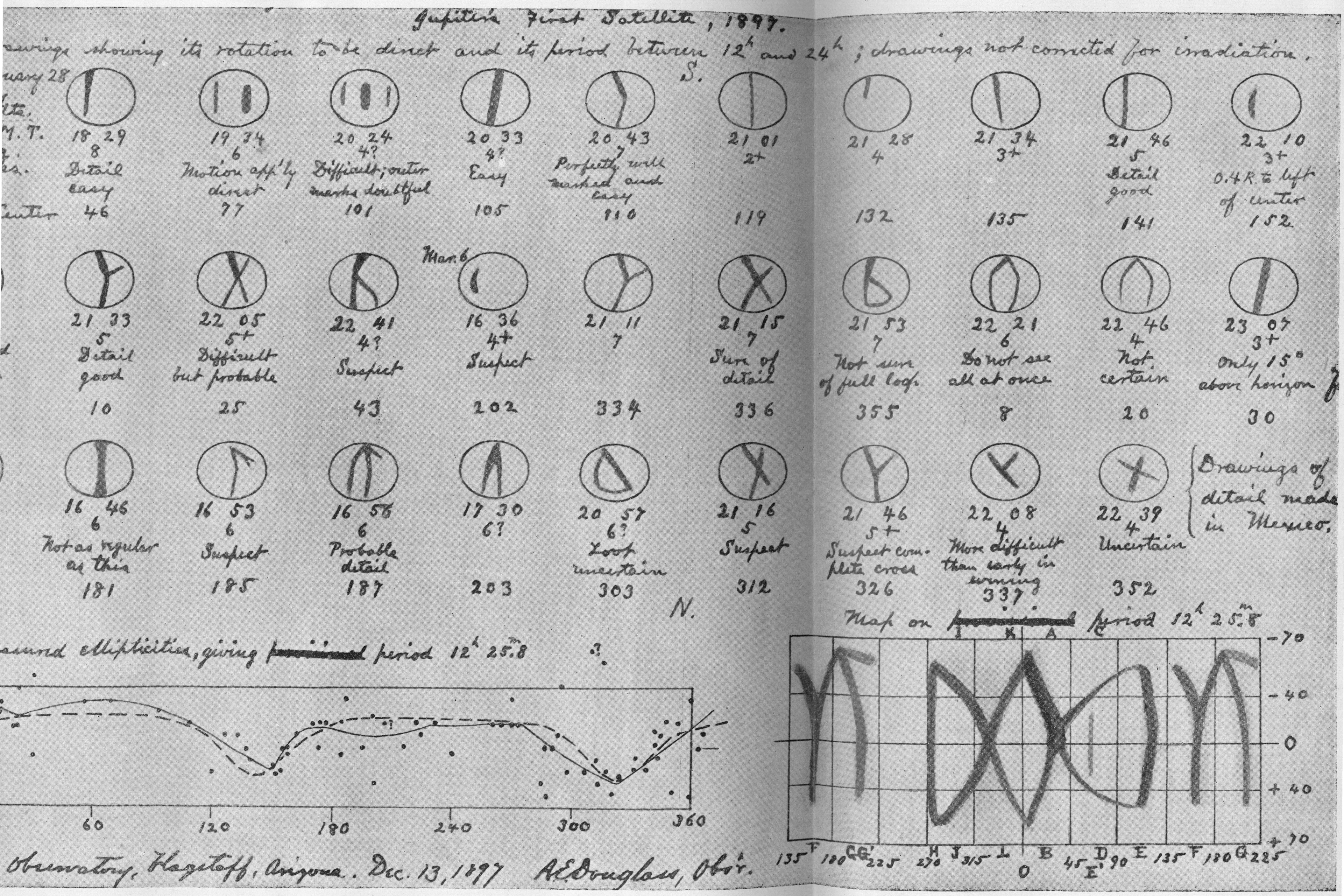
A few almost unique observations have been made upon its form. Upon four nights the satellite has seemed to be not merely elliptical in shape but flatter on the north than on the south limb, and on two other nights it has appeared the reverse. The flattening on the north side was seen periodically on multiples of about $3^d 1^h$ and the two cases of flattening on the south side occurred each on the second day of this period. I made also two observations of this kind at Arequipa which bear this same time-relation to each other (they were the only ones recorded). This can be attributed to actual change in shape or to irradiation effects, but if the latter it is likely that a sensible darkening would have appeared close to the limb. None appeared, and it seems to me doubtful if irradiation could have produced such an outline. The difficulties in attributing it to detail are the same as for the equal flattening at each pole.

I noticed this irregularity in shape a number of times at Arequipa. Upon Oct. 9, 1892, when Prof. W. H. Pickering first saw the elliptical form of this satellite he called me in and asked if I saw anything strange about it. I answered that I saw certain detail, but he, interrupting, asked if it was round. I answered that it was obviously elongated in the direction of its orbit and appeared to be flatter on one side than the other. He, conservatively, considered this departure from the ellipse to be due to some atmospheric effect, but I am now inclined to believe that the flattening was real.

Finally, a few observations were made, upon the shape of the shadow. Three micrometer measurements resulted as follows, in each case the shape of the shadow has been corrected for position on the planet:

1897	Polar	Equatorial	Ellipticity
Mar. 3	0".98	0".98	100
» 10	0.86	0.94	110
» 10	0.87	0.94	109

On Febr. 24 the shadow was recorded as distinctly elliptical when it was central on the planet. In this observation the satellite and shadow were so near together that the former cut off a bit of the north-following edge of the latter. On March 10 when the shadow had almost reached its third contact it was recorded as obviously flattened equatorially. According to the usual meaning of such expressions as used by the writer that would indicate an ellipticity of about 90, but I find that at that time the equatorial



C. Schaidt, Kiel.

diameter was reduced to 0.79 of its real size by foreshortening. So, so far as we can tell from such a record, the real ellipticity was about 110.

These micrometer measures of shadow are rather more below the average scale-measures than the micrometer measures of the satellite itself are above.

To summarize, then, when in transit the effect of the loss of irradiation is very marked but is practically the same at the two poles, and when near the limb of Jupiter the elliptical form is still apparent to the eye; during middle transit no black edgings appear at the poles as would be likely if the poles were entirely dark; no irregularities appear on the north and south limb such as would be caused by dark polar spots; it is doubtful if irradiation or detail can account for the increased flattening of one of the polar limbs; finally, the very shadow is somewhat elliptical. Surface markings probably affect the measures but the apparent ellipticity is undoubtedly due to the real form of the satellite.

Those who have examined Prof. Pickering's classical work on this subject will recollect that the period he obtained from observations of the ellipticities was $13^h 3^m 9^s.3$, retrograde motion, or, less likely, $13^h 3^m 25^s.8$, direct motion (Astronomy and Astrophysics, Nov., 1894, and May, 1893). The changes of form which he observed varied from one in which the equatorial diameter exceeded the other by about 10 per cent, to the circular phase in which the diameters were equal. At times it was observed to go beyond the circular phase and become flattened in its equatorial diameter (Astronomy and Astrophysics, May, 1893).

With regard to his observations in 1894, he says (Astronomy and Astrophysics, Nov., 1894): »The change in shape of the satellite at the time that the circular phase is assumed, is quite marked, and much more rapid than at any other period. (This appears also in my curve for 1897). The name »»circular phase««, although quite applicable in 1892, does not appear to be so at the present time, since the observations show that the ellipse, although it becomes much shortened, never quite reaches the circular shape.« He found that the period of $13^h 3^m$ satisfied his observations for the month of September, 1894 (from his publication I think that $13^h 2^m.6$ might apply still better), and the range of ellipticities obtained by direct comparison with a scale, was at that time from 108 to 120. His observations in the two succeeding months have not been reduced.

Having had a small share in his Arequipa work, I made observations in March, 1895, and obtained a range of ellipticity of 104 to 120 but without enough observations to test the period.

Combining these results with those in 1897, gives the following table:

(3)

Date	Ellipticity	Period	Observer	Locality	Telescope
Dec. 1892	100 to 110	$13^h\ 3^m$	Pickering	Arequipa	13 inch
Oct. 1894	108 » 120	13 3	»	Flagstaff	18 inch
Mar. 1895	104 » 120	?	Douglass	»	»
Mar. 1897	115 » 130	12 25.8	»	Mexico	24 inch

In this there are indications of a distinct increase in the oblateness of this satellite and a decrease in the time of rotation, a combination hard to explain unless accompanied by a decrease in the mean size. Accordingly I have collected recent measures of this satellite in the three following tables. The measures of 1871 are Engelmann's, taken from Young's Astronomy. They are reduced to seconds of arc by considering that at distance 5.2, 1".0 = 2341.2 miles. It is assumed that they are mean diameters. The measures of 1892 are by W. H. Pickering. They were sent to me by letter and will be published in the Annals of Harvard Observatory. The measures of 1894 are by Dr. E. E. Barnard and may be found in Popular Astronomy for October, 1897. They are, he informs me, all polar diameters, that is, perpendicular to the plane of their orbits.

In table (5) I have attempted to bring these uniformly to a mean diameter. The only real changes are in Dr. Barnard's measures; for satellites II, III and IV I have used my own measures in estimating this change; for satellite I, I have used Prof. Pickering's mean ellipticity.

As these are such small bodies, the personal constant for irradiation enters largely into the results, and, to eliminate that as far as possible table (6) is added in which the mean of the diameters of satellites III and IV is a constant. This destroys their value for a determination of the absolute diameters but it nearly, if not quite, removes personal errors from the changing values of the first and second.

The observations of 1871 were made in a 7½ inch telescope at Leipzig; those of 1892 were made in a 13 inch telescope at Arequipa; in 1894 in a 36 inch at Mount Hamilton, and in 1897, in a 24 inch instrument at Mexico.

(4)

	I			II			III			IV		
	Pol.	Mean	Equat.	Pol.	Mean	Equat.	Pol.	Mean	Equat.	Pol.	Mean	Equat.
1871	—	1".07	—	—	0".90	—	—	1".52	—	—	1".26	—
1892	—	1.05	—	—	0.94	—	—	1.42	—	—	1.29	—
1894	1".05	—	—	0".87	—	—	1".52	—	—	1".43	—	—
1897	0.71	—	0".91	0.63	—	0".66	1.33	—	1".34	1.23	—	1".28

(5)

	I			II			III			IV		
	Pol.	Mean	Equat.	Pol.	Mean	Equat.	Pol.	Mean	Equat.	Pol.	Mean	Equat.
1871	—	1.″07	—	—	0.″90	—	—	1.″52	—	—	1.″26	—
1892	—	1.05	—	—	0.94	—	—	1.42	—	—	1.29	—
1894	—	1.11	—	—	0.89	—	—	1.52	—	—	1.46	—
1897	—	0.81	—	—	0.64	—	—	1.34	—	—	1.26	—

(6)

	I			II			III			IV		
1871	—	1.04	—	—	0.88	—	—	1.48	—	—	1.23	—
1892	—	1.05	—	—	0.94	—	—	1.42	—	—	1.29	—
1894	—	1.01	—	—	0.81	—	—	1.38	—	—	1.33	—
1897	—	0.84	—	—	0.67	—	—	1.40	—	—	1.31	—

The results of 1894 depend upon thirty-six measures of, usually, five settings each, with an average residual of about 0.″06 per measure; those of 1897, on seventy-nine measures of six settings each with practically the same average residual per measure. These are distributed almost equally among the four satellites.

In table (6) there is no essential change in III and IV while I and II are very much smaller in the latest measures. From the method of composing this table the relative personal equation is almost entirely eliminated from observations on I and II as stated above but owing to their being slightly smaller than III and IV there may result a differential personal element. That is more likely as the personal element varies more rapidly as the object measured approaches the limit of measurable size.

But in the case of these satellites which are not quite at the limit, such a personal element, if the seeing is good, depends chiefly upon the power employed; but the effect of power is evidently largely negligable because in 1892 and 1897 the power was usually 700 and 750 and on the intermediate date, 1000. I conclude therefore that this change in the first and second satellites is not likely to be due to the effects of personal equation so far as they are yet known. However, it shall be part of my work in the near future to obtain, if possible, direct comparisons with Prof. Pickering and Dr. Barnard.

This decrease in size, if true, supplies the lacking cause. We have, then, first, the decrease in size; second, the increase in rotational velocity; third, the increase in mean polar compression.

Such are the deductions from observations in 1897. The only measures of this satellite not yet reduced and compared are upon the apparent position angle of its major axis but as the total variation was not great, they are not likely to affect any of the results given above.

Lowell Observatory, Flagstaff, Arizona, U. S. A., 1898 March 8. *A. E. Douglass.*