UNIVERSITY OF CALIFORNIA PUBLICATIONS

ASTRONOMY

LICK OBSERVATORY BULLETIN

NUMBER 385

THE LIGHT-VARIATIONS OF THE SATELLITES OF JUPITER AND THEIR APPLICATION TO MEASURES OF THE SOLAR CONSTANT

BY

JOEL STEBBINS

During a sojourn of a month at the Lick Observatory in August and September, 1926, I began a series of measures of the satellites of *Jupiter* with the photo-electric photometer attached to the 12-inch refractor. In these observations I had the very efficient assistance of Messrs. T. S. Jacobsen and N. W. Storer, who after my departure from Mount Hamilton in the middle of September kindly secured additional measures which they have placed at my disposal. The object of the work was to determine whether the satellites could be compared photometrically with nearby stars for tests of the solar variation. Any light changes in the Sun would of course be reflected from all four satellites, and reference to a group of comparison stars would eliminate most of the effect of absorption in the Earth's atmosphere. The idea of testing the constancy of the Sun's radiation by observations of the planets and asteroids is of course an old one, but not to my knowledge has there been any careful study of the satellites of *Jupiter* for this purpose. The planets *Mars*, *Jupiter*, and *Saturn* have been observed photometrically by Guthnick,[1] but of these *Saturn* seems to be the only one which itself is fairly constant in light. With several satellites of *Jupiter* observable, any simultaneous changes in the light of all of them could be attributed to a solar variation. The four bright satellites are of the fifth and sixth magnitude, and ordinarily it should not be difficult to find suitable comparison stars for measurement with the photo-electric photometer.

When I arrived at Mount Hamilton, the photometer had not been in active use for some time, and the first problem was to put it into good working order. The main mechanical features of the instrument are of the first class, and only a few modifications were necessary in the installation. First of all, the wiring was put into metallic conduit separate from all other circuits; also the battery was enclosed in a metal box. One may experiment with open wiring for some time without difficulty, but my experience has been that it is best to put the whole electrical system inside of a grounded metal covering, and then no trouble from stray electric charges will arise.

At first there seemed to be a large contact potential of the grounding key, but after some experimenting this turned out to be due to a charge on the fine natural amber support of the contact plate. In the dry summer air at Mount Hamilton, the conditions are perfect for any object holding a charge, so this insulating piece of amber after once picking up a charge would hold it indefinitely. The difficulty was removed by wrapping tin foil about most of the amber surface. Also another stray charge was found on the string of the grounding mechanism, which entered the cell box through a hard rubber bushing. The friction of the string on the rubber was producing a charge, which would leak off in several seconds, but it would induce a large effect on the cell and electrometer system. The substitution of a metal wire for the string eliminated this trouble. These may seem like small items, but the successful performance of an electrostatic instrument like the photo-electric photometer depends upon attention to just these details.

Another matter was the question of a good ground connection. As the 110-volt A. C. lighting circuit of the observatory has the neutral side connected to the

[1] *A. N.*, **206**, 157, 1918; **208**, 105, 1919; **212**, 39, 1920.

water pipes, I preferred not to mix up with that system, and we simply connected to the mounting of the 12-inch telescope which seemed to have enough capacity to be used instead of the earth.

Although the fine conditions on the mountain may continue for many days and nights, it is necessary to force dry air into the cell box in damp weather. A new drying apparatus was installed, consisting of a calcium-chloride "tower," two wash bottles with sulfuric acid, and a bulb of glass wool. With this arrangement a very slow bubbling of air into the instrument from the tank seemed to give perfect insulation of the cell and connections.

For potential we used fresh radio "B" batteries, 310 volts on the cell, and 45 volts on each side of the electrometer. The best battery that I know of for this purpose is made up of modified standard Carhart cells, but repeated comparative tests have shown that ordinary dry cells give a steady enough voltage, provided the potential is not forced up too near the glowing point of the photo-electric cell.

The sensitivity attained with the installation in 1926 may be measured by the photo-electric effect from a star of magnitude 1.0 and spectrum A0, which was about 2.5 volts per second as compared with 0.10 volts per second in 1915.[2] This increase of twenty-five fold has been due to the work of several persons. A number of mechanical features are from the ideas of Dr. Elmer Dershem, but the fundamental improvement is that of the quartz photo-electric cell developed by Professor Jakob Kunz of the University of Illinois.

After my arrival on August 11 we made a few observations the same evening, though it required several days to get the photometer going. Regular observations were begun on August 16, but it was not until August 23 or 24 that everything was finally on a fairly permanent basis. Although this delay of a week or more seemed pretty long at the time, it was a reasonably prompt solution of the difficulties involved.

The program for a set of measures on the satellites of *Jupiter* was soon adopted as follows. Readings, usually six, were taken on each of the available satellites, then on the four comparison stars, then again on the satellites. A second set would repeat the measures in reverse order, and a third set would repeat the first. The main problem was to eliminate the effect of the sky background, lighted up by the planet itself. The diaphragm at the focus of the telescope objective has an aperture of 90″, or about twice the apparent diameter of *Jupiter*. It was found feasible to observe the satellites down to a distance of about 100″ from the planet's center, but this required great care in the setting, and constant checking on the guiding of the instrument. After each group of readings on a satellite, the telescope was turned off in declination, first to one side and then to the other, and sky readings were taken with the satellite just out of the field. In the extreme case of a satellite near the planet, and our own bright Moon near *Jupiter*, the sky effect would amount to one-fourth or even one-third of the total. In these circumstances more time was spent in measuring the sky than the satellites.

Very often two satellites would be in the field at once, and their combined light could be measured, but unless they were quite close together so that the sky correction could be easily determined, the observation was not attempted. This frequent disturbance of the measures of one satellite by the proximity of another, or of the planet itself, necessarily reduces the total number of observations that can be made to advantage. In the beginning it was not attempted to observe Satellite I, but after some practice a few measures were made of it near elongation.

A diaphragm smaller than 90″ diameter might be used without encroaching upon the beam of light from a celestial object, but this would require the repeated withdrawal and re-insertion of a slide, and accurate following by the driving clock. The mounting of the 12-inch refractor is some forty years old or more, and while it performs perhaps as well as it ever did, the clamp and slow motion in right ascension are worked by ropes, and there is a certain clumsiness in all manipulations of the telescope. A modern mounting with clamps and slow motions at the eye-end, setting-dial for right ascension, and electric dome control, would reduce the observing time to about one-half what it is with the present arrangements.

But there remains the California sky. What a luxury it is to take some measures of an object, to turn off and not come back to it for half an hour or more, and then to find the second set of readings agreeing within one or two per cent of the first ones! Moreover, these conditions last all night, and the next night, and again the next. During my stay of thirty-three nights on the mountain, thirty were clear, and though during two or three of these there were passing thin clouds, all of the thirty nights would have been called first-class on the standards of the Mississippi Valley.

As *Jupiter* was moving slowly in the sky during the period of observation, it was possible to select four comparison stars which would practically eliminate the atmospheric extinction. The data from the Henry Draper Catalogue are as shown in Table I.

Considerable attention has been paid to the correction for differential atmospheric extinction. It is sufficient to use the reduction to no atmosphere to be of the form $0^m\!.20\, f \sec z$, where z is the apparent zenith distance, $0^m\!.20$ the approximate visual extinction at the

[2] *Lick Obs. Bull.*, **8**, 186, 1916.

TABLE I

COMPARISON STARS

		R.A. 1900	Decl. 1900	Visual magnitude	Photo-electric magnitude	Spectrum	
(1)	ι Capricorni	21^h 16°7	−17° 16′	4^{m}30	5^{m}00	K0	
(2)	γ Capricorni	21 34.6	−17 07	3.80	5.50	Fp	With sector 1^{m}5
(3)	42 Capricorni	21 36.1	−14 29	5.28	5.83	G5	
(4)	μ Capricorni	21 47.8	−14 01	5.18	5.38	F0	

zenith, and f a factor which varies with the spectral type of the star, and with changing transparency of the air. Because of the uniform excellence of the sky at Mount Hamilton, and the relatively small variation in zenith distance during the measures, the transparency was assumed to be the same on all nights.

The variation of f with spectral type can be determined roughly from the regular measures of the comparison stars, in particular stars (1) and (4) which are farthest apart in position, and are of spectra K0 and F0 respectively. From the variation of the difference of magnitude between these two stars with changing hour angle there was found,

Star	Spectrum	Extinction factor f	Transmission at Zenith
(4)	F0	0.95	0.839
(1)	K0	0.82	0.859

These values of the transmission may be compared with Abbot's values of the zenith transmission at Mount Wilson,[3] 0.830 for 4500A and 0.873 for 5000A respectively. The maximum sensitivity of a quartz-potassium cell for constant energy along the spectrum is about at 4600A. The satellites were assumed to be of spectrum G, like the Sun, and a factor $f=0.88$ was used for them, although our Moon is known to have a color-index about equivalent to K0.

Except for the principle of the thing, it would have been sufficient simply to ignore the extinction, because of the favorable grouping of the comparison stars. The differential extinction between *Jupiter* and the mean of the four amounted to a hundredth of a magnitude on only two or three occasions, the average correction for the entire series being only 0^{m}004.

In Table II are the observations of the satellites and comparison stars. The day begins at Greenwich midnight. The angle α is the jovicentric elongation of the Earth from the Sun, or what we may call the solar phase of the satellites. The magnitudes of the satellites and comparison stars are referred to the mean of the latter, adopted to be 5.46, and have already been corrected for atmospheric extinction. Except for this small correction, the magnitudes are given exactly as they came out in the reductions.

TABLE II

JOURNAL OF OBSERVATIONS

1926 G. C. T.	α	Satellites				Comparison Stars				Remarks
		I	II	III	IV	(1)	(2)	(3)	(4)	
Aug. 16.318	0°24			(5^{m}127)	(6^{m}247)	5^{m}147	5^{m}491	5^{m}773	5^{m}431	Tests, reject.
16.342	0.24			(5.147)	(6.197)	5.133	5.461	5.793	5.453	Tests, reject.
17.343	0.40		5^{m}977	5.214	6.216	5.125	5.483	5.786	5.444	
17.407	0.41		5.935	5.173	6.208	5.087	5.499	5.797	5.455	
18.365	0.60		5.713			5.087	5.495	5.829	5.428	
20.303	1.00		5.926	5.126	6.171	5.126	5.487	5.771	5.458	
20.337	1.01		5.947	5.101	6.183	5.134	5.487	5.781	5.438	
21.315	1.22			5.160	6.237	5.112	5.477	5.790	5.463	
21.339	1.22			5.179	6.233	5.103	5.478	5.801	5.459	
22.406	1.46		(5.777)		(6.284)	5.098	5.434	5.834	5.475	Trouble with photometer, reject.
23.316	1.65					5.092	5.488	5.802	5.458	Bright Moon.
24.286	1.86		6.042	5.259	6.328	5.110	5.497	5.779	5.454	
24.317	1.87		6.056	5.267	6.309	5.123	5.467	5.788	5.462	
24.382	1.88		6.013	5.229	6.279	5.141	5.472	5.774	5.454	
25.306	2.08			5.223	6.302	5.117	5.475	5.782	5.466	
25.331	2.08			5.208	6.324	5.118	5.490	5.781	5.450	
25.397	2.10		5.790	5.231	6.311	5.120	5.469	5.789	5.464	
26.360	2.31					5.132	5.462	5.786	5.459	Fog interfered.
Aug. 26.390	2.31		5.829	5.173		5.117	5.474	5.784	5.466	

[3] *The Sun*, p. 297.

TABLE II—(*Cotninued*)

1926	G. C. T.	α	Satellites I	II	III	IV	Comparison Stars (1)	(2)	(3)	(4)	Remarks
Aug.	27.261	2°49	...	$5^{m}959$	$5^{m}166$	$6^{m}348$	$5^{m}130$	$5^{m}477$	$5^{m}785$	$5^{m}448$	
	27.289	2.50	...	5.978	5.166	6.350	5.129	5.479	5.784	5.450	
	27.330	2.51	...	5.990	5.175	6.343	5.128	5.472	5.785	5.453	
	28.275	2.71	...	...	5.226	6.364	5.129	5.472	5.793	5.447	
	28.300	2.71	...	...	5.229	6.367	5.126	5.475	5.782	5.456	
	28.344	2.72	...	...	5.236	6.363	5.128	5.490	5.779	5.442	
	29.331	2.93	...	5.810	...	6.388	5.140	5.483	5.779	5.437	
	29.371	2.94	...	5.808	...	6.390	5.121	5.477	5.793	5.449	
	31.264	3.34	...	6.075	5.330	6.428	5.116	5.479	5.789	5.456	
	31.294	3.34	...	6.079	5.321	6.434	5.130	5.471	5.789	5.448	
	31.343	3.35	...	6.110	5.337	6.451	5.127	5.483	5.779	5.450	
Sept.	1.264	3.55	...	...	5.285	6.460	5.129	5.479	5.785	5.448	
	1.290	3.55	...	...	5.295	6.465	5.133	5.483	5.790	5.432	
	1.331	3.56	...	...	5.311	6.457	5.114	5.481	5.798	5.445	
	2.253	3.75	...	5.832	...	6.466	5.123	5.492	5.779	5.445	
	2.309	3.76	...	5.846	...	6.477	5.116	5.477	5.799	5.448	II incomplete.
	2.357	3.77	...	...	(5.280)	...	...	...	...	...	From II+III, reject.
	3.242	3.95	...	5.985	5.201	...	5.111	5.486	5.781	5.462	
	3.271	3.95	...	5.994	5.205	...	5.134	5.475	5.783	5.451	
	3.313	3.96	...	5.989	5.204	...	5.117	5.478	5.800	5.444	
	4.261	4.15	...	6.048	5.270	6.452	5.123	5.493	5.782	5.444	
	4.278	4.16	...	6.058	...	...	...	...	...	...	II incomplete.
	4.301	4.16	...	...	5.274	6.448	5.129	5.482	5.781	5.448	
	4.342	4.17	...	...	5.275	6.458	5.100	5.491	5.794	5.454	
	5.253	4.35	...	5.836	...	6.438	5.120	5.475	5.785	5.460	
	5.290	4.36	5.858	5.845	...	6.441	5.124	5.477	5.790	5.450	
	5.335	4.37	5.824	5.815	...	6.439	5.141	5.490	5.765	5.443	
	6.233	4.55	5.947	...	5.375	6.436	5.132	5.478	5.783	5.446	
	6.265	4.55	5.969	...	5.367	6.448	5.129	5.497	5.783	5.433	
	6.309	4.56	6.002	...	5.361	6.425	5.112	5.468	5.800	5.459	
	7.235	4.74	5.817	6.115	5.371	6.452	5.109	5.479	5.796	5.454	
	7.269	4.75	5.830	6.121	5.367	6.458	5.128	5.479	5.777	5.457	
	7.331	4.76	5.810	6.146	5.394	6.472	5.113	5.477	5.800	5.448	
	8.232	4.93	6.046	...	5.335	6.443	5.113	5.487	5.787	5.452	
	8.263	4.94	6.049	...	5.360	6.454	5.122	5.479	5.791	5.449	
	8.314	4.95	6.044	...	5.355	6.473	5.108	5.478	5.800	5.452	
	9.222	5.12	5.828	...	...	...	...	...	...	...	I incomplete.
	9.237	5.13	...	5.867	...	6.495	5.129	5.489	5.789	5.431	
	9.275	5.13	...	5.865	...	6.490	5.127	5.472	5.781	5.460	
	9.294	5.14	...	...	5.290	...	...	...	...	...	From I+III.
	9.317	5.14	...	5.875	...	6.503	5.132	5.479	5.781	5.447	
	9.340	5.14	...	...	5.286	...	...	...	...	...	From IV.
	10.270	5.32	...	6.007	5.251	6.541	5.139	5.489	5.765	5.447	
	10.315	5.33	...	6.016	5.250	6.527	5.102	5.497	5.781	5.458	
	11.235	5.50	...	6.136	5.303	...	5.107	5.471	5.806	5.450	From II+IV.
	11.267	5.51	...	6.104	5.304	...	5.115	5.474	5.800	5.450	From II+IV.
	11.303	5.52	...	6.097	5.315	...	5.127	5.478	5.788	5.446	From II+IV.
	13.253	5.89	5.964	(5.891)	5.430	6.576	5.112	5.506	5.776	5.447	II incomplete, reject.
	13.311	5.90	5.997	...	5.417	6.557	5.124	5.481	5.802	5.433	
	14.217	6.06	5.876	6.157	5.489	6.577	5.127	5.471	5.792	5.448	III half weight.
	14.266	6.07	5.886	6.135	5.425	6.598	5.142	5.476	5.792	5.430	
	21.288	7.28	...	...	5.485	...	5.086	5.486	5.807	5.461	
	22.214	7.42	6.095	...	5.464	6.624	5.089	5.491	5.794	5.468	
	22.259	7.43	6.123	...	5.463	6.615	5.135	5.486	5.775	5.443	
	24.218	7.73	6.165	...	5.352	6.619	5.105	5.463	5.825	5.448	
	24.260	7.74	(6.129)	...	(5.288)	(6.564)	5.154	5.468	5.788	5.429	Poor, rejected.
	25.227	7.88	...	6.266	5.378	6.647	5.108	5.481	5.794	5.456	
Sept.	25.292	7.89	...	6.259	5.383	6.660	5.127	5.476	5.817	5.420	

TABLE II—(*Continued*)

1926 G. C. T.	α	Satellites I	II	III	IV	Comparison Stars (1)	(2)	(3)	(4)	Remarks
Sept. 28.197	8°32	....	$6^{\rm m}129$	$5^{\rm m}513$	....	$5^{\rm m}126$	$5^{\rm m}508$	$5^{\rm m}783$	$5^{\rm m}426$	
28.253	8.33	....	6.187	5.546	....	5.155	5.484	5.764	5.435	
30.201	8.60	6.009	5.975	....	6.699	5.096	5.457	5.820	5.469	
30.256	8.60	5.996	5.991	....	6.757	5.100	5.487	5.789	5.463	
Oct. 5.216	9.24	....	6.205	5.587	6.864	5.119	5.486	5.798	5.437	
6.232	9.36	....	....	5.613	6.821	5.085	5.480	5.820	5.454	
8.198	9.57	6.257	....	5.479	6.781	5.117	5.467	5.803	5.455	
18.178	10.49	6.145	6.155	....	7.001	5.098	5.473	5.831	5.437	
20.178	10.63	....	6.427	5.726	6.974	5.114	5.453	5.819	5.453	
23.163	10.82	....	6.359	5.579	....	5.078	5.465	5.819	5.477	
26.201	10.99	....	....	5.742	6.882	5.105	5.483	5.791	5.460	
27.168	11.04	....	6.476	5.763	6.897	5.116	5.467	5.802	5.456	
Dec. 11.028	9.96	(6.585)	....	....	7.297	....	....	5.812	5.440	I poor, rejected.
20.019	9.23	....	....	5.927	7.252	5.101	5.467	5.819	5.454	

For comparison of results on different dates, the next step is to reduce all magnitudes to standard or mean opposition. This is accomplished by the formula:

$$\text{Reduction to mean opposition} = 5 \log r_0\Delta_0/r\Delta,$$

where r is the heliocentric and Δ the geocentric distance of *Jupiter*, and $r_0 = 5.2028$, $\Delta_0 = 4.2028$. A table of this correction was made, of which the following is the skeleton:

TABLE III

REDUCTION TO MEAN OPPOSITION

1926	Aug. 14	$+0^{\rm m}159$
	22	+ .158
	30	+ .147
	Sept. 7	+ .125
	15	+ .096
	23	+ .058
	Oct. 1	+ .014
	9	− .034
	17	− .087
	25	− .141
	Nov. 2	− .196

In Table IV the results for each satellite are brought together; the date in the first column identifies the corresponding observation in Table II. The second column contains the orbital phase computed from the time of superior conjunction of the satellite with *Jupiter*, as given in the *American Ephemeris*. Each magnitude in the third column is obtained from the one in Table II by applying the proper correction from Table III. The fourth column contains the correction for the solar phase α, which will be discussed later. The reduced magnitudes in the fifth column are derived from the two preceding columns. The residuals in the sixth column are based upon the final light-curves, and in the seventh column these residuals are averaged for each date.

TABLE IV

REDUCED MAGNITUDES

SATELLITE I

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Sept. 5	51°7	$5^{\rm m}989$	$-0^{\rm m}068$	$5^{\rm m}921$	$+0^{\rm m}013$	....
5	60.8	5.955	− .068	5.887	− .012	0.000
6	243.6	6.075	− .071	6.004	.000	....
6	250.1	6.097	− .071	6.026	.000	....
6	259.1	6.130	− .071	6.059	+ .008	+ .003
7	87.6	5.942	− .073	5.869	− .007	....
7	94.5	5.955	− .074	5.881	+ .010	....
7	107.1	5.934	− .074	5.860	− .005	− .001
8	290.6	6.167	− .076	6.091	+ .001	....
8	296.9	6.170	− .077	6.093	+ .002	....
8	307.3	6.165	− .077	6.088	− .001	+ .001
9	132.2	5.946	− .080	5.866	+ .002	+ .002
13	232.8	6.067	− .091	5.976	.000	....
13	244.6	6.100	− .091	6.009	.000	.000
14	69.0	5.975	− .094	5.881	− .011	....
14	79.0	5.985	− .094	5.891	+ .008	− .002
22	257.0	6.157	− .115	6.042	− .002	....
22	266.1	6.185	− .115	6.070	+ .004	+ .001
24	304.8	6.217	− .120	6.097	+ .007	+ .007
24	313.4	6.181	− .120	6.061	(−.027)	....
30	82.6	6.028	− .133	5.895	+ .016	....
30	93.8	6.014	− .133	5.881	+ .009	+ .012
Oct. 8	270.0	6.228	− .148	6.080	+ .008	+ .008
18	140.7	6.051	− .162	5.889	+ .021	+ .021
Dec. 11	292.9	6.125	− .154	5.971	(−.119)	....

SATELLITE II

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Aug. 17	309°8	$6^{\rm m}137$	$-0^{\rm m}013$	$6^{\rm m}124$	$0^{\rm m}000$	....
17	316.3	6.095	− .013	6.082	− .022	$-0^{\rm m}011$
18	53.6	5.873	− .019	5.854	− .016	− .016
20	250.3	6.085	− .032	6.053	− .021	....
20	253.7	6.106	− .032	6.074	− .009	− .015
22	103.8	5.935	− .045	5.890	(+.034)	....
24	294.6	6.198	− .057	6.141	− .001	....
24	297.8	6.212	− .057	6.155	+ .014	....
24	304.4	6.169	− .057	6.112	− .022	− .003

TABLE IV—(*Continued*)

SATELLITE II

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Aug. 25	47°.4	5^{m}944	−0^{m}064	5^{m}880	0^{m}000	0^{m}000
26	148.2	5.982	− .069	5.913	+ .014	+ .014
27	236.6	6.111	− .074	6.037	.000	.....
27	239.4	6.130	− .075	6.055	+ .007	.....
27	243.6	6.142	− .075	6.067	+ .009	+ .005
29	86.7	5.958	− .086	5.872	+ .023	.....
29	90.7	5.956	− .086	5.870	+ .021	+ .022
31	282.9	6.219	− .096	6.123	− .015	.....
31	285.9	6.223	− .096	6.127	− .013	.....
31	290.9	6.254	− .096	6.158	+ .016	− .004
Sept. 2	124.7	5.971	− .106	5.865	− .001	.....
2	130.4	5.985	− .106	5.879	+ .005	+ .002
3	225.1	6.122	− .111	6.011	+ .010	.....
3	228.0	6.130	− .111	6.019	+ .007	.....
3	232.3	6.125	− .111	6.014	− .010	+ .002
4	328.5	6.182	− .115	6.067	.000	.....
4	330.2	6.192	− .115	6.077	+ .015	+ .005
5	69.2	5.967	− .119	5.848	− .008	.....
5	73.0	5.976	− .120	5.856	+ .003	.....
5	77.5	5.946	− .120	5.826	− .025	− .010
7	270.3	6.240	− .128	6.112	− .008	.....
7	273.8	6.246	− .128	6.118	− .008	.....
7	280.0	6.270	− .128	6.142	+ .006	− .003
9	113.4	5.985	− .135	5.850	− .006	.....
9	117.3	5.983	− .135	5.848	− .011	.....
9	121.6	5.993	− .136	5.857	− .006	− .008
10	218.3	6.121	− .139	5.982	− .006	.....
10	222.9	6.130	− .139	5.991	− .005	− .006
11	316.2	6.247	− .142	6.105	.000	.....
11	319.5	6.214	− .142	6.072	− .022	.....
11	323.1	6.207	− .142	6.065	− .015	− .012
13	161.0	5.994	− .149	5.845	(−.071)	.....
14	258.8	6.256	− .152	6.104	+ .008	.....
14	263.7	6.234	− .152	6.082	− .024	− .008
25	295.4	6.313	− .177	6.136	− .006	.....
25	302.3	6.306	− .177	6.129	− .007	− .006
28	237.0	6.160	− .181	5.979	− .060	.....
28	242.6	6.217	− .181	6.036	− .020	− .040
30	80.1	5.994	− .183	5.811	− .039	.....
30	85.7	6.009	− .183	5.826	− .023	− .031
Oct. 5	228.7	6.194	− .189	6.005	− .007	− .007
18	102.7	6.061	− .196	5.865	+ .014	+ .014
20	305.4	6.319	− .197	6.122	− .010	− .010
23	247.8	6.231	− .197	6.034	− .035	− .035
27	313.8	6.321	− .198	6.123	+ .012	+ .012

SATELLITE III

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Aug. 16	244°.1	5^{m}287	−0^{m}008	5^{m}279	(−0^{m}093)	.....
16	245.3	5.307	− .008	5.299	(− .073)	(−0^{m}083)
17	295.8	5.384	− .014	5.370	+ .012	.....
17	299.1	5.333	− .014	5.319	− .036	− .012
20	85.2	5.285	− .034	5.251	+ .013	.....
20	86.9	5.260	− .034	5.226	− .014	.000
21	136.2	5.318	− .042	5.276	− .022	.....
21	137.4	5.337	− .042	5.295	− .003	− .012
24	286.1	5.415	− .061	5.354	− .010	.....
24	287.7	5.423	− .061	5.362	− .001	.....

TABLE IV—(*Continued*)

SATELLITE III

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Aug. 24	290°.9	5^{m}385	−0^{m}061	5^{m}324	−0^{m}038	−0^{m}016
25	337.6	5.378	− .067	5.311	− .001	.....
25	338.8	5.362	− .067	5.295	− .016	.....
25	342.2	5.385	− .068	5.317	+ .009	− .003
26	32.2	5.326	− .074	5.252	+ .014	+ .014
27	76.2	5.318	− .079	5.239	+ .010	.....
27	77.6	5.318	− .079	5.239	+ .008	.....
27	79.6	5.327	− .080	5.247	+ .015	+ .011
28	127.3	5.376	− .086	5.290	+ .002	.....
28	128.6	5.379	− .086	5.293	+ .003	.....
28	130.8	5.386	− .086	5.300	+ .008	+ .004
31	278.1	5.474	− .103	5.371	+ .003	.....
31	279.6	5.465	− .103	5.362	− .006	.....
31	282.1	5.481	− .103	5.378	+ .012	+ .003
Sept. 1	328.5	5.427	− .108	5.319	− .007	.....
1	329.8	5.437	− .108	5.329	+ .005	.....
1	331.9	5.452	− .109	5.343	+ .023	+ .007
2	23.4	5.419	− .114	5.305	(+.053)	.....
3	68.3	5.338	− .119	5.219	− .003	.....
3	69.7	5.341	− .119	5.222	− .001	.....
3	71.9	5.340	− .119	5.221	− .003	− .002
4	119.7	5.404	− .124	5.280	+ .002	.....
4	121.7	5.408	− .124	5.284	+ .004	.....
4	123.8	5.409	− .124	5.285	+ .001	+ .002
6	219.1	5.503	− .133	5.370	+ .006	.....
6	220.7	5.495	− .133	5.362	− .003	.....
6	223.0	5.489	− .133	5.356	− .010	− .002
7	269.6	5.496	− .138	5.358	− .014	.....
7	271.4	5.492	− .138	5.354	− .017	.....
7	274.5	5.518	− .138	5.380	+ .010	− .007
8	319.9	5.456	− .142	5.314	− .022	.....
8	321.5	5.481	− .143	5.338	+ .004	.....
8	324.1	5.476	− .143	5.333	+ .003	− .005
9	12.5	5.408	− .147	5.261	− .009	.....
9	14.6	5.404	− .147	5.257	− .009	− .009
10	62.7	5.365	− .151	5.214	− .006	.....
10	64.9	5.364	− .151	5.213	− .008	− .007
11	111.3	5.414	− .155	5.259	− .010	.....
11	112.9	5.414	− .155	5.259	− .011	.....
11	114.7	5.425	− .155	5.270	− .003	− .008
13	213.0	5.533	− .164	5.369	+ .007	.....
13	216.0	5.520	− .164	5.356	− .007	.000
14	261.6	5.588	− .167	5.421	+ .048	.....
14	264.1	5.524	− .167	5.357	− .016	+ .005
21	258.0	5.552	− .191	5.361	− .013	− 0.13
22	304.7	5.526	− .193	5.333	− .019	.....
22	307.0	5.525	− .193	5.332	− .017	− .018
24	45.6	5.404	− .198	5.206	− .020	− .020
24	47.7	5.340	− .198	5.142	(−.080)	.....
25	96.4	5.425	− .201	5.224	− .026	.....
25	99.7	5.430	− .201	5.229	− .026	− .026
28	246.1	5.544	− .208	5.336	− .037	.....
28	248.9	5.576	− .208	5.368	− .005	− .021
Oct. 5	239.6	5.576	− .221	5.355	− .016	− .016
6	290.7	5.596	− .223	5.373	+ .011	+ .011
8	29.6	5.450	− .225	5.225	− .015	− .015
20	272.4	5.618	− .237	5.381	+ .010	+ .010
23	62.4	5.451	− .239	5.212	− .008	− .008
26	215.2	5.594	− .241	5.353	− .010	− .010
27	263.8	5.608	− .241	5.367	− .006	− .006
Dec. 20	86.9	5.433	− .221	5.212	− .028	− .028

TABLE IV—(*Continued*)

SATELLITE IV

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Aug. 16	$145^{\circ}6$	$6^{m}407$	$-0^{m}015$	$6^{m}392$	$(-0^{m}003)$	....
16	146.1	6.357	− .015	6.342	(− .053)	$(-0^{m}028)$
17	167.9	6.376	− .025	6.351	− .028	....
17	169.3	6.368	− .026	6.342	− .036	− .032
20	232.1	6.330	− .063	6.267	− .046	....
20	232.8	6.342	− .064	6.278	− .035	− .040
21	254.1	6.395	− .076	6.319	+ .012	....
21	254.6	6.391	− .076	6.315	+ .008	+ .010
22	277.7	6.442	− .090	6.352	(+.041)	....
24	318.5	6.484	− .114	6.370	+ .038	....
24	319.2	6.465	− .114	6.351	+ .019	....
24	320.6	6.435	− .115	6.320	− .012	+ .015
25	340.7	6.457	− .126	6.331	− .008	....
25	341.2	6.478	− .126	6.352	+ .012	....
25	342.6	6.465	− .128	6.337	− .003	.000
27	23.0	6.500	− .149	6.351	+ .003	....
27	23.7	6.502	− .150	6.352	+ .004	....
27	24.5	6.495	− .151	6.344	− .004	+ .001
28	45.0	6.514	− .162	6.352	.000	....
28	45.6	6.517	− .162	6.355	+ .003	....
28	46.5	6.513	− .162	6.351	− .001	+ .001
29	67.9	6.536	− .174	6.362	.000	....
29	68.8	6.538	− .175	6.363	.000	.000
31	109.8	6.572	− .196	6.376	− .012	....
31	110.5	6.578	− .196	6.382	− .006	....
31	111.6	6.595	− .196	6.399	+ .010	− .003
Sept. 1	131.5	6.602	− .207	6.395	− .002	....
1	132.1	6.607	− .207	6.400	+ .003	....
1	133.0	6.598	− .207	6.391	− .006	− .002
2	153.0	6.605	− .217	6.388	− .004	....
2	154.2	6.616	− .218	6.398	+ .006	+ .001
4	196.5	6.586	− .237	6.349	.000	....
4	197.4	6.582	− .238	6.344	− .005	....
4	198.3	6.592	− .238	6.354	+ .008	+ .001
5	218.0	6.569	− .247	6.322	− .002	....
5	218.8	6.572	− .247	6.325	+ .002	....
5	219.8	6.570	− .248	6.322	.000	.000
6	239.3	6.564	− .256	6.308	− .002	....
6	240.0	6.576	− .256	6.320	+ .011	....
6	240.9	6.553	− .257	6.296	− .012	− .001
7	261.0	6.577	− .266	6.311	+ .004	....
7	261.7	6.583	− .266	6.317	+ .010	....
7	263.1	6.596	− .266	6.330	+ .023	+ .012
8	282.6	6.564	− .275	6.289	− .024	....
8	283.3	6.575	− .275	6.300	− .013	....
8	284.4	6.594	− .275	6.319	+ .005	− .011
9	304.4	6.613	− .284	6.329	+ .004	....
9	305.2	6.608	− .284	6.324	− .001	....
9	306.1	6.621	− .284	6.337	+ .011	+ .005
10	326.8	6.655	− .293	6.362	+ .027	....
10	327.8	6.641	− .293	6.348	+ .012	+ .020
13	31.4	6.679	− .317	6.362	+ .013	....
13	32.7	6.660	− .318	6.342	− .007	+ .003
14	52.3	6.676	− .324	6.352	− .002	....
14	53.4	6.697	− .325	6.372	+ .018	+ .008
22	225.4	6.686	− .377	6.309	− .009	....
22	226.4	6.677	− .377	6.300	− .017	− .013
24	268.8	6.671	− .388	6.283	− .025	− .025
24	269.7	6.616	− .389	6.227	(− .082)	....
25	290.6	6.694	− .394	6.300	− .017	....
25	292.0	6.707	− .394	6.313	− .005	− .011

TABLE IV—(*Continued*)

SATELLITE IV

1926	Orbital phase	At mean opposition	Reduction for α	Reduced magnitude	Residual	Mean residual
Sept. 30	$38^{\circ}2$	$6^{m}718$	$-0^{m}418$	$6^{m}300$	$-0^{m}050$	....
30	39.4	6.775	− .418	6.357	+ .007	− .022
Oct. 5	146.8	6.853	− .438	6.415	+ .020	+ .020
6	168.8	6.804	− .441	6.363	− .016	− .016
8	211.4	6.752	− .448	6.304	− .026	− .026
18	66.4	6.907	− .472	6.435	+ .073	+ .073
20	109.5	6.866	− .476	6.390	+ .004	+ .004
26	239.6	6.734	− .485	6.249	− .060	− .060
27	260.5	6.742	− .486	6.256	− .051	− .051
Dec. 11	142.7	6.851	− .459	6.392	− .004	− .004
20	335.1	6.758	− .438	6.320	− .018	− .018

In the discussion of the observational data in tables II and IV, we begin with the comparison stars. Dividing the measures into two series, and taking the general means, there is found for the photo-electric magnitudes:

TABLE V

MAGNITUDES OF COMPARISON STARS

1926	(1)	(2)	(3)	(4)
Aug. 16–Sept. 14	$5^{m}119$	$5^{m}480$	$5^{m}789$	$5^{m}451$
P.E. one observation	±.009	±.007	±.008	±.007
Sept. 21–Oct. 27	5.110	5.478	5.802	5.450
P.E. one observation	±.014	±.010	±.013	±.011

The average probable errors for the two groups are $\pm 0^{m}008$ and $\pm 0^{m}012$, and hence for the mean of four stars in a set are $\pm 0^{m}004$ and $\pm 0^{m}006$ respectively. These probable errors were derived from all the observations, good, poor, and indifferent, and as the comparison stars show absolutely no indication of variability, the mean of four of them may be considered as a satisfactory standard of reference. The mean residuals of the comparison stars for each date are shown in fig. 2.

The opposition of *Jupiter* occurred on August 15, and it was a week or more later before the photometer was in the best condition; then the full Moon came along close to *Jupiter* and made observations difficult. For these reasons the results from August 16 to 23 are considered as of less weight than those from August 24 to September 14, though the transition from fair to good measures was presumably gradual. After September 14 the observations were taken only at odd times, and they have been used to determine the general trend of the light of the satellites with increasing solar phase.

The corrected magnitudes for the satellites in the third column of table IV all exhibit the same phenomenon—a light-variation in the orbital period superimposed upon a brightening up at the full phase of opposition, similar to that of our Moon. These two effects may be disentangled by successive approximations. A rough guess is made as to the variation of a satellite with solar phase α, all observations are then corrected for this variation, and the resulting magnitudes are plotted according to the orbital phase. The light-curve in the orbital period is then drawn, and the residuals give a second determination of the solar-phase effect. The original observations are then corrected anew for the solar-phase effect, a second orbital light-curve is determined, and so on. As the orbital variation is represented more easily by a free-hand curve than by any simple formula, there is no advantage in a least-squares solution at any step. Elementary considerations show that the light received by a satellite from *Jupiter* is negligible compared with that received from the Sun.

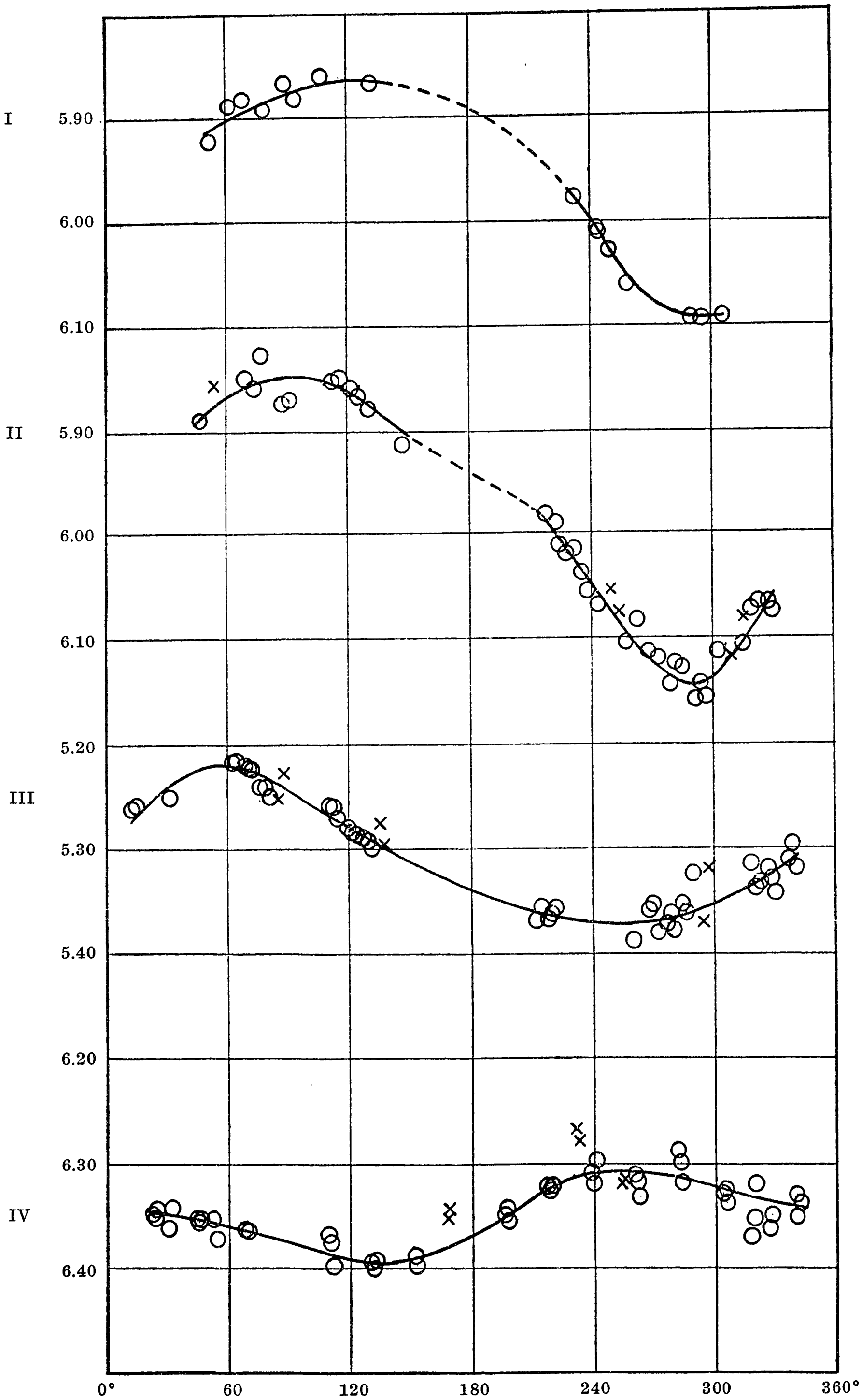

Fig. 1. Variations of the Satellites of *Jupiter* with Orbital Phase.

It has been found by Mueller[4] that the visual magnitudes of superior planets and asteroids may be represented near opposition as linear functions of the solar phase. For the present measures of *Jupiter's* satellites, however, a second-degree term can be added which expresses the variation as

$$m = m_0 + b\alpha + c\alpha^2,$$

where m is the magnitude at solar phase α expressed in degrees, b and c are empirical constants, and m_0 is the magnitude at opposition.

After some trials the following expressions were adopted for the different satellites. The measures of satellite I were not begun until three weeks after opposition, so a linear relation is sufficient for that case.

$$\begin{aligned} \text{Satellite I,} \quad & m = m_0 + 0.0155\,\alpha \\ \text{II,} \quad & m = m_0 + 0.0337\,\alpha - 0.00143\,\alpha^2 \\ \text{III,} \quad & m = m_0 + 0.0347\,\alpha - 0.00116\,\alpha^2 \qquad \text{(A)} \\ \text{IV,} \quad & m = m_0 + 0.065\,\alpha - 0.0019\,\alpha^2 \end{aligned}$$

In the fourth column of table IV the reduction for α is the sum of the two terms in (A), but with reversed sign. The magnitudes in the fifth column are thus reduced to zero solar phase and are ready for the determination of the orbital variations. The light-curves for the satellites are given in fig. 1, where it is seen that each has the sort of variation which we might expect from a body of non-uniform surface brightness keeping one face toward the primary. The results for satellite I agree better than was expected from the proximity to *Jupiter;* II and III give satisfactory curves; but with its longer period the variation of IV is not so well determined. The period and range for each satellite may be summarized as follows:

TABLE VI

Satellite	Period	Range	Phase of maximum	Phase of minimum
I	$1^{d}77$	$0^{m}229$	122°	295°(?)
II	3.55	0.294	90	292
III	7.17	0.155	58	255
IV	16.75	0.090	255	135

It may be noted that I, II, and III are in a general way brighter on the front side in their motion, while IV is brighter on the rear side.

We now return to the variation with solar phase, which is shown in fig. 2. The computed curves are simply the graphs of the fourth column of table IV, while the plotted magnitudes are derived by subtracting these reversed sums from the mean residuals in the fifth column of that table. As already noted, the measures beginning with about August 24, or $\alpha = 2°$, were of the best quality, and it was this middle series which was used in deriving the orbital light-curves. Although the first observations are not of great weight, each of the satellites II, III, and IV, shows a greater increase of light near opposition than is represented by the second-degree expression in α.

In table VII are brought together the residuals by nights for satellites II, III, and IV. These discordances include the errors in the original measures, the errors in the correction for atmospheric extinction, the errors in the assumed variation of the satellites with the orbital and solar phase, and finally the variations of the Sun itself, all referred to the mean of the four comparison stars. Any change in the solar radiation would be reflected in all of the satellites simultaneously. The residuals of the first week are systematically negative, as mentioned before, so there remain some twenty nights beginning with August 24. From these there is found an average residual of ±0.004 magnitude, which indicates no change in the Sun which could be detected during this short interval of three weeks. The latter measures from September 21 to October 27 are not sufficient to show anything but the general character of the variation of the satellites, and the two observations in December are of still less weight.

TABLE VII

Mean Residuals by Nights

1926		II	III	IV	Mean	Remarks
Aug.	17	$-^{m}011$	$-^{m}012$	$-^{m}032$	$-^{m}018$	
	18	− 16	....	....	− 16	
	20	− 15	0	− 40	− 18	All poor
	21	....	− 12	+ 10	− 1	
Aug.	24	− 3	− 16	+ 15	− 1	
	25	0	− 3	0	− 1	
	26	+ 14	+ 14	....	+ 14	Poor, one set only
	27	+ 5	+ 11	+ 1	+ 6	
	28	....	+ 4	0	+ 2	
	29	+ 22	....	0	+ 11	
	31	− 4	+ 3	− 3	− 1	
Sept.	1	....	+ 7	− 2	+ 2	
	2	+ 2	....	+ 1	+ 2	
	3	+ 2	− 2	....	0	
	4	+ 8	+ 2	+ 1	+ 4	
	5	− 10	....	0	− 5	
	6	....	− 2	− 1	− 2	
	7	− 3	− 7	+ 12	+ 1	
	8	....	− 5	− 11	− 8	
	9	− 8	− 9	+ 5	− 4	
	10	− 6	− 7	+ 20	+ 2	
	11	− 12	− 8	....	− 10	
	13	....	0	+ 3	+ 2	
	14	− 8	+ 5	+ 8	+ 2	

The average deviation for a night, ±0.004 magnitude, found in the best part of the present work, represents about what might be expected under good conditions in a long series for tests of the solar constant

[4] *Potsdam Publ.*, **8**, 366, 1893.

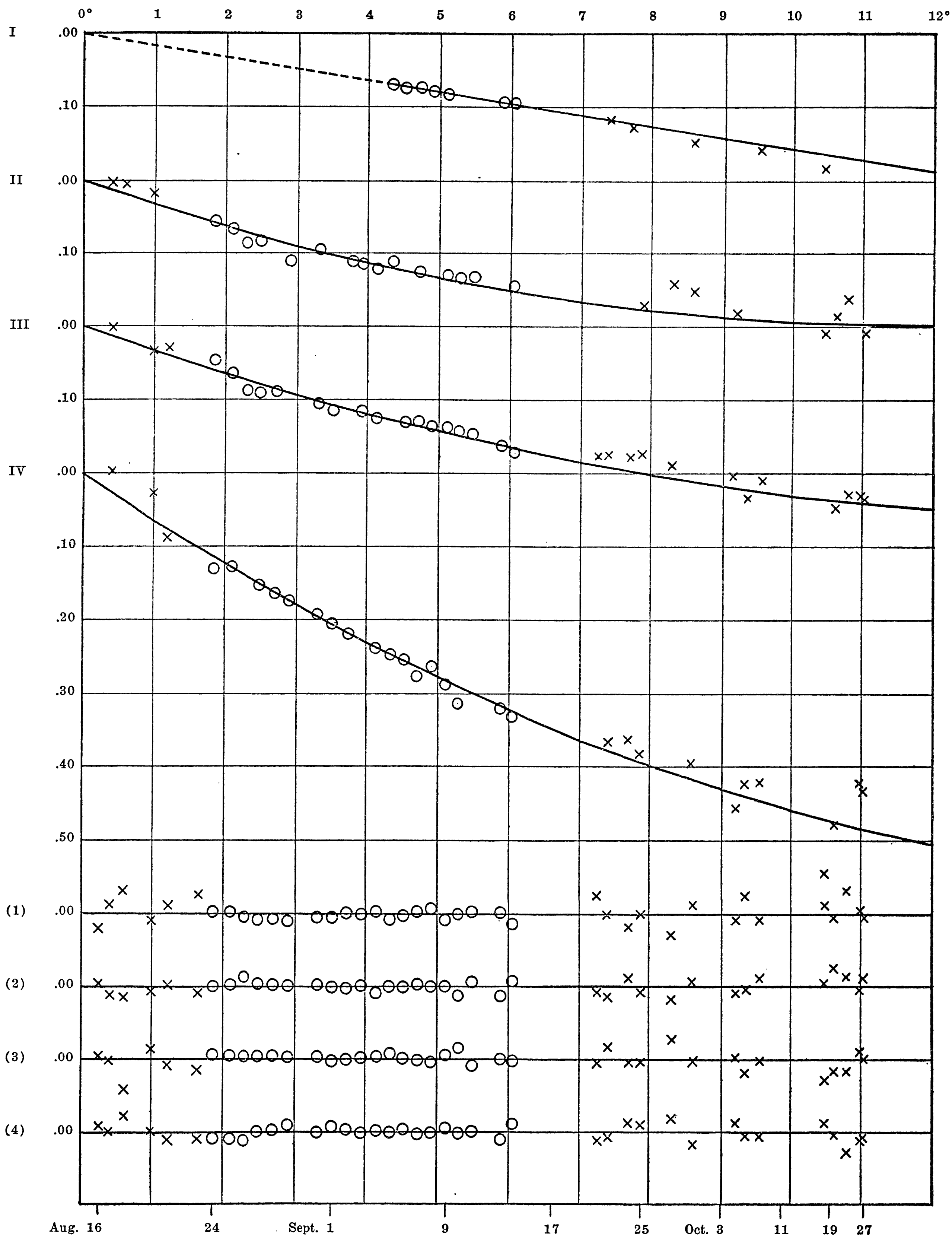

Fig. 2. Variations of the Satellites of *Jupiter* with Solar Phase; Comparison Stars.

by this method. With average errors of say four-tenths of one per cent, a solar variation of one or two per cent inside of a week ought not to escape detection, and these results could be used for confirmation of the short-period variations found by the Smithsonian observers. We should expect that the solar variation at 4600A, the region of maximum sensitivity of the photo-electric cell, would vary more than the total radiation which makes up the solar constant.

In the 1926 opposition, *Jupiter* was pretty far south, the declination being $-17°$. Succeeding oppositions will be more and more favorable for northern latitudes, but this advantage will be offset in part by the dates running into the winter season. In 1927 there will be ample opportunity to get a long series before opposition, which comes on September 22.

We now turn to a comparison with the previous photometric observations of the satellites of *Jupiter*. The results of visual observers, extending over half a century, have been brought together by Guthnick in *Astronomische Nachrichten*, **198**, 233, 1914. The wriggly curves there exhibited for the satellites of *Jupiter* and the inner satellites of *Saturn* are not particularly convincing, but the variation of *Iapetus* with a range of 1.5 magnitudes is within reach of visual photometers. The inadequacy of visual observations is evidenced by their failure to show the conspicuous solar-phase effect, ranging from 0.2 to 0.5 magnitude for different satellites. Even when only differential measures on the satellites themselves are made, satellite IV should show a discrepancy of 0.3 magnitude from the others, because of its greater solar-phase coefficient. The solar-phase variation of the planet *Jupiter* has been determined photo-electrically by Guthnick (see table VIII), with of course satisfactory precision.

The present conclusion that the four bright satellites have light-variations in conformity with each keeping one side toward the planet is in complete disagreement with the observations of Professor W. H. Pickering on the forms of the satellites. In his recent paper[5] on the third satellite he finds an ellipticity of 1.05 or more and a semi-period of rotation 3.5 hours, which would give a corresponding light-variation of five per cent. All I can say is that the light-variations observable with the photo-electric photometer are much smaller than anything that my own eye would be capable of in detecting elliptical forms of planetary disks, of whatever size.

We now compare the solar phase-effect of these satellites with the same phenomenon for other bodies. Following Mueller it has been customary to define the "phase-coefficient" as the change in magnitude per degree change in solar phase, but because of the terms in a^2 the present results are not strictly comparable with those where a linear relation was assumed. A rough comparison may be made by assuming the phase-coefficient to be one-tenth of the sum of the a and a^2 terms for 10°. When this is done, we have the following:

[5] *Publ. A. S. P.*, **37**, 191, 1925.

TABLE VIII

	Phase-Coefficient magnitude per degree	Authority
Jupiter I	0.016	This paper.
II	.019	
III	.023	
IV	.046	
Jupiter	.015	Guthnick, *Astronomische Nachrichten*, **206**, 157, 1918.
Mercury	.037	Mueller, 1893. *Potsdam Publications*, **8**, 366,
Venus	.013	Mueller, 1893.
Mars	.015	Mueller, 1893.
Moon	.022	Russell, *Astrophysical Journal*, **43**, 114, 1916.
Mean of 30 asteroids	.030	Mueller, *Photometrie der Gestirne*, p. 379.

The coefficients for *Jupiter* and his satellites are photo-electric; the others are visual. It will be noted that the phase-effect for the inner three satellites does not much exceed that for *Jupiter*, being slightly less than that of the Moon, while the fourth satellite flashes out much more; its coefficient would rank high even for an asteroid.

Summary

The present series of photo-electric measures of the four bright satellites of *Jupiter* shows that each one is variable in its period of revolution, and also exhibits a flashing up at the full phase. These phenomena are readily explained by the assumption that the periods of rotation and revolution of each satellite are the same and that each has a rough, irregularly spotted surface like the Moon.

Comparison of the satellites with a group of four stars gives a test of the constancy of the solar radiation with the effect of the Earth's atmosphere practically eliminated. During three weeks of continuous observation, the mean residual for a night was ± 0.004 magnitude, or four-tenths of one per cent, an accordance which shows that this is a promising method for tests of the Sun.

I am much indebted to Dr. Aitken and other members of the observatory staff for courtesies extended during the course of this work.

Madison, Wisconsin,
January, 1927.

Issued March 10, 1927.