THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME LXV | JANUARY 1927 | NUMBER 1

MEASUREMENT OF THE VELOCITY OF LIGHT BETWEEN MOUNT WILSON AND MOUNT SAN ANTONIO[1]

By A. A. MICHELSON
Research Associate of the Carnegie Institution
Assisted by F. Pearson

ABSTRACT

The following is a continuation of the experiments described in the *Astrophysical Journal*, **60**, 256, 1924. The arrangement of apparatus differs slightly from that of the former investigation, allowing a more nearly normal incidence on the facets of the revolving mirror, and providing greater symmetry as well as increase in illumination.

Five independent series of measurements made with different revolving mirrors (one of steel having the form of a prism with eight facets, and another with twelve, and three of glass with eight, twelve, and sixteen facets) gave results showing a remarkable agreement.

The final result for the velocity of light *in vacuo* is 299,796 km per second.

The increasing appreciation of the importance of this fundamental constant of nature and the anticipation of the possibility of attaining a considerable increase in accuracy in its measurement justified the acceptance of the generous invitation of Dr. G. E. Hale, then director of the Mount Wilson Observatory, to make use of the facilities there available. It is with sincere appreciation that I take this opportunity of extending my acknowledgment of the many courtesies received and of the cordial co-operation of Dr. Hale and subsequently of Dr. Adams and the entire staff of the Observatory.

The result of the preliminary experiments described in a previ-

[1] *Contribution from the Mount Wilson Observatory*, No. 329.

ous article[1] gave for the final value of the velocity of light in air 299,735 km per second.

The correction[2] to *vacuum* is given by

$$n-1=(n_0-1)\frac{d}{d_0}=(n_0-1)\frac{p}{p_0}\frac{T_0}{T}$$

$$\frac{p}{p_0}=.822$$

and

$$\frac{T_0}{T}=.932\ ,$$

whence

$$n-1=.000294\times .765$$

or

$$n=1.000225\ ,$$

giving 67 km for the correction.[3]

Accordingly, for the preliminary determination

$$V=299{,}735+67$$

or

$$V=299{,}802\ .$$

A second series of observations with the glass octagon was begun in July of 1925, the arrangement of apparatus being essentially the same as in the preliminary work, except that instead of driving the electric fork ($N=132$) by make and break between platinum points, the fork ($N=528$) was driven by a vacuum-tube circuit, giving a rate far more nearly constant.

This rate was measured by comparison with a free pendulum furnished by the United States Coast and Geodetic Survey, as in the previous work; but with an important improvement in the stroboscopic method. This consists in allowing the light from a very narrow slit to fall on a mirror attached to the pendulum, forming, by means of a good achromatic lens, an image of the slit in the plane of an edge of the fork, where it is observed by an eyepiece.

[1] *Astrophysical Journal*, **60**, 256, 1924.

[2] The correction should be applied to the individual observations; but the result is not appreciably altered by taking the mean values given above.

[3] This was erroneously given as 85 km in the article cited.

This method of making the stroboscopic comparison was found to be far more convenient and accurate than that described in the work of last year.

As before, the octagonal mirror making 528 turns per second rotates through one-eighth of a turn during the time of passage of light from the revolving mirror to the distant station and return, thus presenting the succeeding face of the mirror to the returning beam at (very nearly) the same angle as at rest.

The observations consist, then, in increasing the speed of the revolving mirror until the stroboscopic image between fork and mirror is stationary, at which instant the measurement is taken of the small angle α_1 by which the displacement of the image differs from 90°. The direction of rotation is then reversed, and a similar series of observations furnishes the angle α_2. If $\alpha = \alpha_1 + \alpha_2$, then the angle through which the mirror rotates during the time required for light to travel through the distance $2D$ will be $\pi/4 - \alpha/4$, and the velocity is given by $V = (16ND)/(1 - \alpha/\pi)$.

If $1/n$ is the period of the (optical) beats between the fork and the pendulum and $1/\nu$ that of the coincidences between the C.G.S. pendulum and the true seconds, and if N is the nearest whole number (in the present instance 528), then, as both α and ν are small,

$$V = \frac{16D}{1-\nu}(N+n)\left(1+\frac{\alpha}{\pi}\right) ,$$

or since α and n are small,

$$V = \frac{16 \times 35425.15 \times 528}{1 - .00051}\left(1+\frac{\alpha}{\pi}+\frac{n}{N}\right) \qquad D = 35425.1$$

$$V = 299{,}425\left(1+\frac{\alpha}{\pi}+\frac{n}{N}\right) .$$

Table I gives the results of ten series of observations with the glass octagon.

These results, as well as those previously published[1] are to be regarded as preliminary. The definitive measurements were begun in June, 1926, and continued until the middle of September.

[1] *Astrophysical Journal*, **60**, 256, 1924.

TABLE I

TEN SERIES OF OBSERVATIONS

	a/π	n/N	V_a
I	0.00077	0.00013	299,695
II	.00057	.00015	299,651
III	.00044	.00038	299,671
IV	.00037	.00047	299,677
V	.00054	.00045	299,722
VI	.00047	.00043	299,695
VII	.00032	.00068	299,725
VIII	.00017	.00070	299,686
IX	.00018	.00076	299,707
X	0.00021	0.00058	299,662
Mean velocity in air			299,689
Correction			+67
V in vacuo			299,756

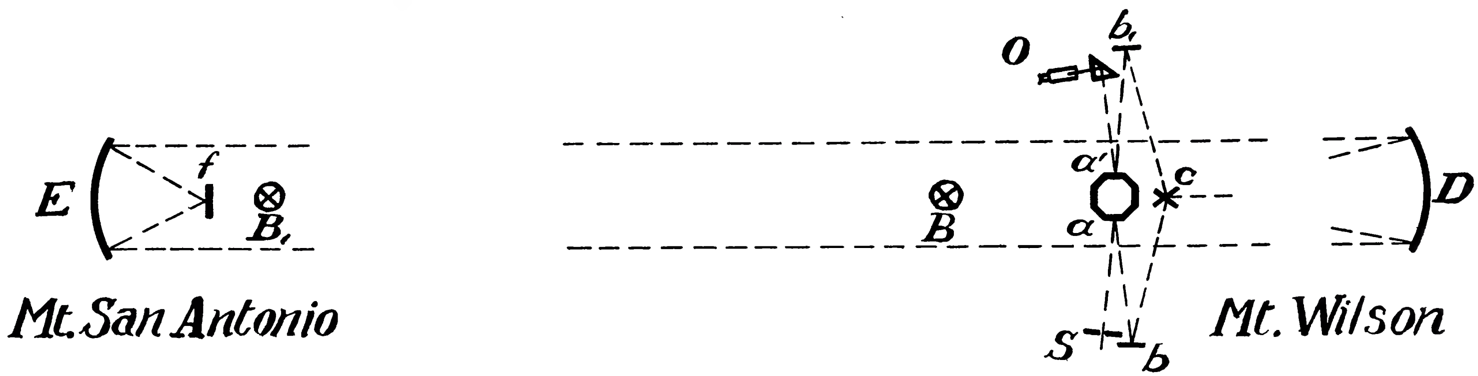


FIG. 1.—Arrangement of apparatus

The arrangement of apparatus at the home station was slightly different as shown in Figure 1, the advantage being an increase in intensity in consequence of greater effective width of the light beam falling on the revolving mirror at nearly normal incidence, as well as greater symmetry.

With this layout a series of observations with the same small glass octagon gave the results recorded in Table II. The numbers

TABLE II

	a	*b*	*c*	*V*	Wt.
I	0.00059	0.00028	0.00072	299,747	2
II	.00046	.00040	.00073	299,747	2
III	.00045	.00038	.00073	299,738	3
IV	.00057	.00036	.00072	299,762	3
V	.00047	.00033	.00073	299,729	3
VI	.00052	.00038	.00073	299,759	3
VII	.00061	.00041	.00073	299,792	1
VIII	.00048	.00038	.00072	299,744	4
IX	.00049	.00036	.00072	299,741	4
X	.00047	.00040	.00072	299,747	4
XI	.00044	.00042	.00072	299,744	4
XII	0.00042	0.00042	0.00073	299,741	4
Weighted mean	....	....	....	299,746	....
Correction	....	....	....	+67	....
Velocity *in vacuo*	....	....	....	299,813	....

given are the means of three series of observations, each series containing six (double) observations.

On account of the small values of $a=\alpha/\pi$, $b=n/N$, and $c=\nu$, the formula for the velocity may be written

$$V=16DN(1+a+b+c) .$$

With $D=35{,}425$ and $N=528$, this gives

$$V=299270+V(a+b+c) .$$

The results with the glass octagon are shown in Table II.

Giving these three results the weights 1, 2, and 5, respectively, the weighted mean of all the observations with the glass octagon is $V=299{,}797$.

DEFINITIVE MEASUREMENTS

Toward the close of the work of the summer of 1925 an attempt was made to attain a speed of rotation of 528 turns per second with a glass octagon nearly twice as large as that used in the experiments just described. Owing probably to some defect in the glass, it burst at a speed of 400, thus terminating the work. In order to provide against a repetition of such an accident four mirrors were constructed. Two of these were of glass, of about the same construction, but twice as large, as the small octagon, a photograph of which is given in Figure 2. The first of these had twelve facets and the second sixteen; the diameters being $6\frac{1}{4}$ and $7\frac{1}{2}$ cm, respectively, and the speed of rotations 350 and 264. The flat end of the steel axle on which the glass mirrors are mounted rests on a steel flat with a small aperture for oil, under pressure a trifle less than that which would lift it from its bearing. The driving power is furnished by an air blast issuing through two nozzles and impinging on the vanes of a paddle wheel.

Regulation of the speed was obtained by a counterblast controlled by a valve by means of which the speed could be kept constant for several seconds (as indicated by the immobility of the stroboscopic image) quite sufficient for the measurement of the corresponding small displacement of the image.

The other two mirrors were of nickel steel and furnished by Mr. Elmer A. Sperry. A photograph of the first, an octagon, is shown in Figure 3.

The driving power is furnished by an air blast from four nozzles impinging on the buckets attached to the axle.[1] The flat end of the latter rests on a single ball-bearing.

All four mirrors gave excellent results notwithstanding the fact that time was insufficient for the attainment of very great accuracy in the surfaces. This was particularly noticeable in the steel mirrors, the lack of homogeneity making the process of polishing and figuring much more difficult than in the case of the glass mirrors.[2]

[1] The mirrors actually employed were provided with duplicate bucket wheels and nozzles, allowing of reversal of the direction of rotation.

[2] All are now in process of refiguring in preparation for a resumption of operations during the winter, when atmospheric conditions are likely to be more favorable.

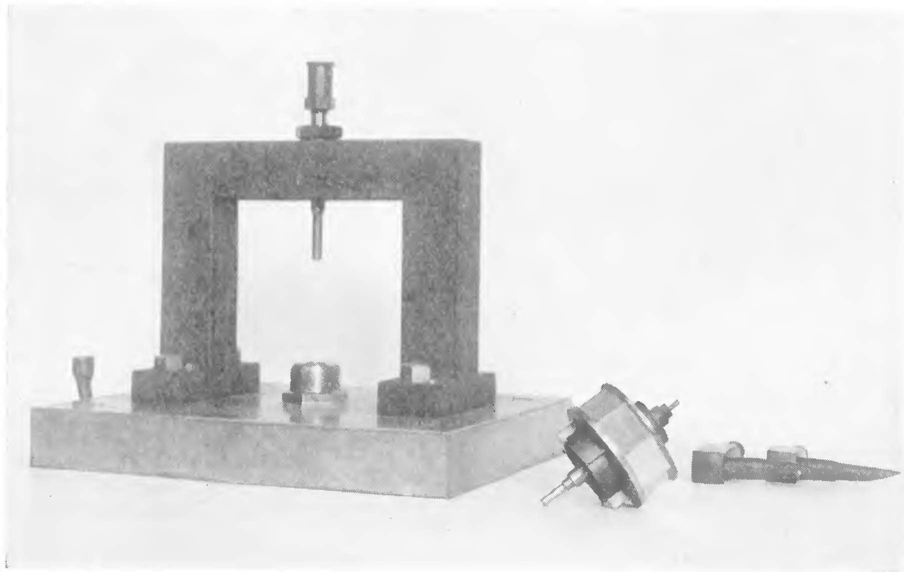


FIG. 2*a*.—The small octagon detached from its mounting

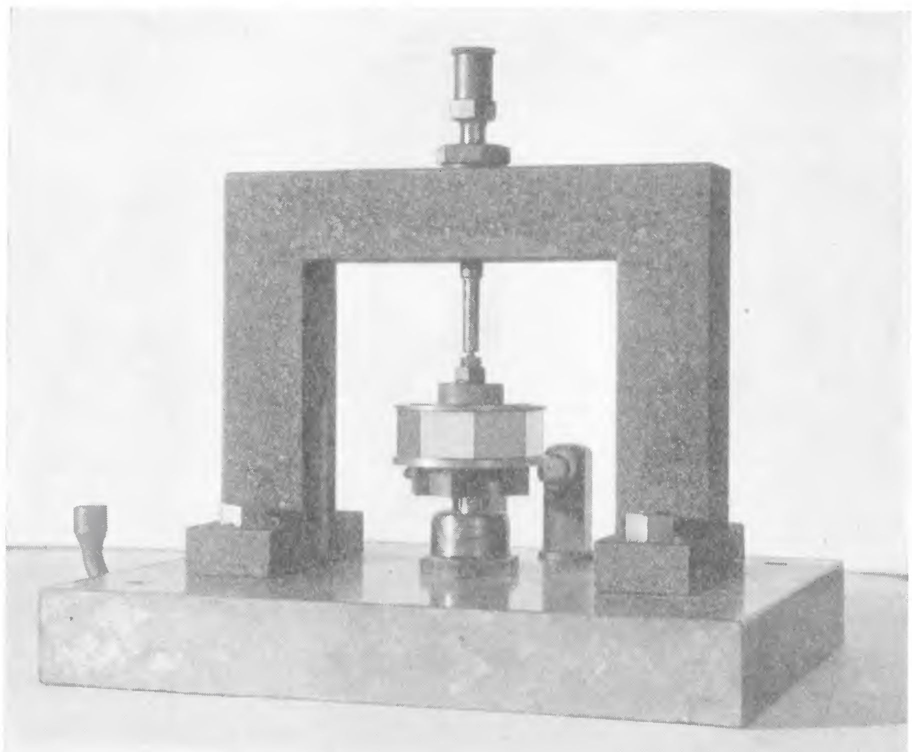


FIG. 2*b*.—The small octagon in its mounting

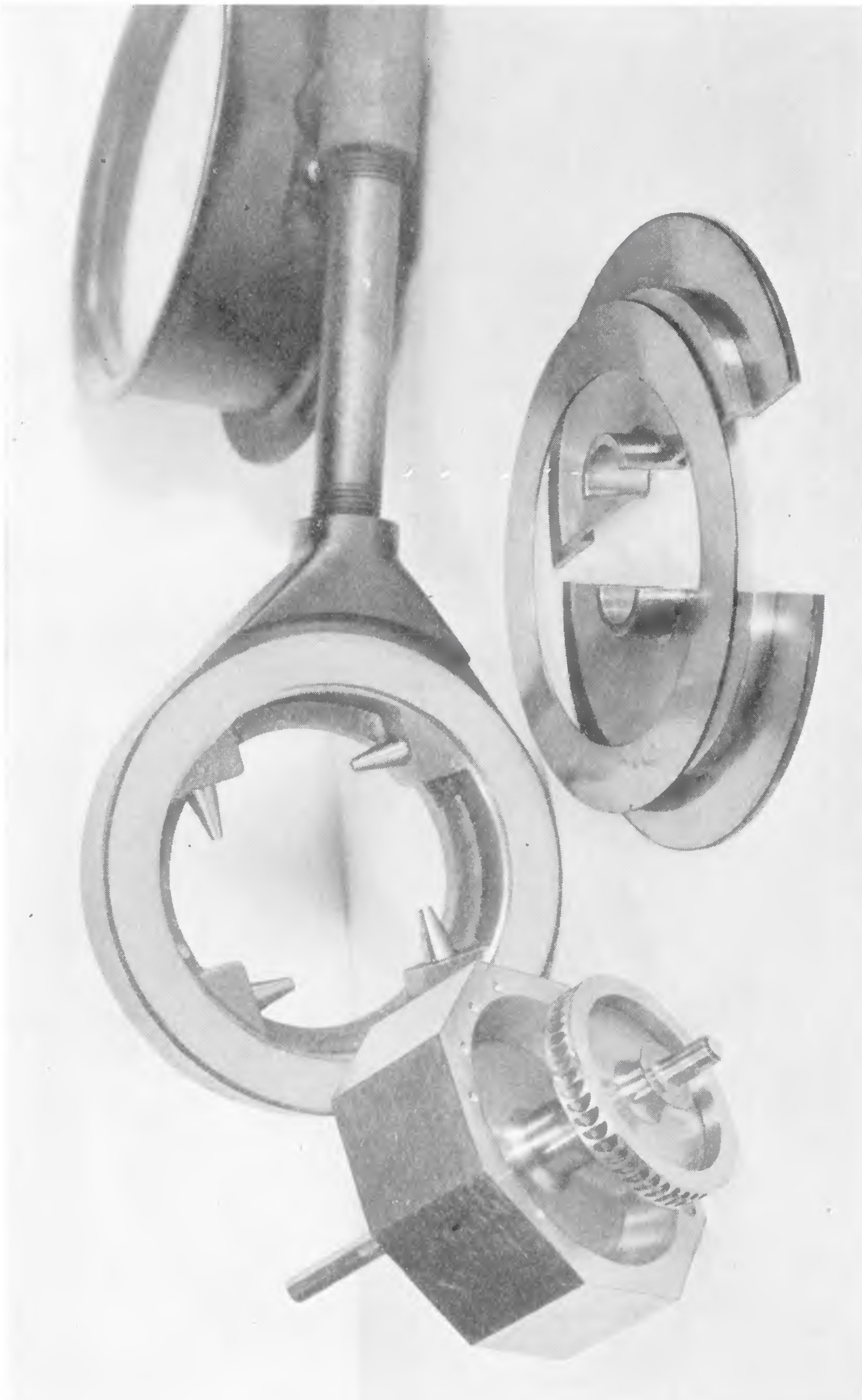


FIG. 3.—The octagon of nickel steel furnished by Mr. Sperry

With a glass twelve-facet mirror and the layout of apparatus and method of procedure essentially the same as in last year's work, the following results were obtained:

$$V=\frac{24DN}{1-\nu}(N+n)\left(1+\frac{3\alpha}{2\pi}\right)$$

or if

$$\frac{3\alpha}{2\pi}=a\quad \frac{n}{N}=b$$

and

$$-\nu=c\qquad D=35424.5$$
$$r=53\text{ cm}$$
$$V=299{,}265+3(a+b+c)\ .$$

The results obtained are shown in Table III.

TABLE III

TWELVE-FACET GLASS MIRROR

	a	*b*	*c*	*VS*	*V*	Wt.
I	−0.00018	0.00100	0.00075	471	299,736	1
II	.00047	.00040	.00073	480	299,745	3
III	.00058	.00026	.00073	471	299,733	3
IV	.00022	.00061	.00072	465	299,730	3
V	.00012	.00062	.00071	435	299,700	1
VI	− .00007	.00088	.00073	462	299,727	5
VII	.00020	.00098	.00073	453	299,718	5
VIII	.00004	.00085	.00073	462	299,727	5
IX	.00009	.00100	.00073	492	299,757	1
X	− .00021	.00114	.00074	501	299,766	2
XI	.00050	.00037	.00074	483	299,748	2
XII	.00071	.00009	.00073	459	299,724	5
XIII	.00052	.00034	.00073	477	299,742	5
XIV	.00003	.00073	.00075	453	299,718	5
XV	0.00004	0.00071	0.00075	450	299,715	5
Weighted mean	....	....	....	....	299,729	....
Correction	....	....	....	....	+67	....
Velocity *in vacuo*	....	....	....	....	299,796	....

A series of measurements with the glass sixteen-facet mirror the formula for which is

$$V=\frac{32DN}{1+2\,\alpha/\pi}\qquad \begin{matrix}D=35424.5\\ \gamma=55\text{ cm}\end{matrix}$$

gave the results shown in Table IV.

TABLE IV

	a	b	c	VS	V	Wt.
I_{I}	0.00159	−0.00089	0.00076	438	299,703	.....
I_{II}	.00115	− .00033	.00076	474	299,739	
I	$(2\times I_{II}+I_{I})/3$	....	....	.....	299,727	1
II	.00051	.00045	.00071	501	299,766	2
III	.00038	.00052	.00071	483	299,748	2
IV_{I}	.00006	.00073	.00071	450	299,715	.....
IV_{II}	.00079	− .00006	.00073	438	299,703	
IV	$(2\times IV_{II}+IV_{I})/3$	....	....	.....	299,707	5
V	.00090	− .00009	.00073	462	299,727	5
VI_{I}	.00111	− .00029	.00072	462	299,727	.....
VI_{II}	.00074	.00013	.00072	477	299,742	
VI	$(2\times VI_{II}+VI_{I})/3$	....	....	.....	299,737	4
VII	.00085	.00011	.00072	504	299,769	3
VIII	.00097	− .00013	.00069	459	299,724	2
IX	.00104	.00008	.00070	498	299,763	2
X	.00081	.00002	.00071	450	299,715	4
XI	.00091	.00007	.00071	465	299,730	4
XII	.00112	.00027	.00069	462	299,727	2
XIII	.00117	.00027	.00069	477	299,742	2
XIV	.00098	.00009	.00070	477	299,742	3
XV	0.00104	−0.00009	0.00070	495	299,760	3
Weighted mean	....	....	....	.....	299,736	.....
Correction	....	....	....	.....	+67	.....
Velocity *in vacuo*	....	....	....	.....	299,803	.....

A second series with the glass sixteen-facet mirror gave the results summarized in Table V.

TABLE V

	a	b	c	VS	V	Wt.
I	0.00067	0.00029	0.00071	501	299,766	1
II	.00019	.00060	.00073	456	299,721	5
III	.00020	.00061	.00073	462	299,727	5
IV	.00053	.00029	.00074	468	299,733	1
V	.00039	.00034	.00075	444	299,709	5
VI	.00049	.00029	.00075	459	299,724	5
VII	.00066	.00009	.00073	444	299,709	2
VIII	.00064	.00010	.00073	441	299,706	2
IX	.00078	.00006	.00074	474	299,739	3
X	.00102	− .00015	.00072	477	299,742	3
XI	.00053	.00025	.00073	453	299,718	3
XII	.00059	.00018	.00072	447	299,712	1
XIII	0.00071	0.00023	0.00072	498	299,763	1
Weighted mean	....	....	....	....	299,722	......
Correction	....	....	....	....	+67	......
Velocity *in vacuo*	....	....	....	....	299,789	......

A series of measurements with the steel twelve-facet mirror gave the results shown in Table VI.

TABLE VI

	a	*b*	*c*	*VS*	*V*	Wt.
{ I_{I}	0.00063	0.00016	0.00072	453	299,718 }	.....
{ I_{II}	.00030	.00046	.00072	444	299,709 }	
I	$(2\times I_{II}+I_{I})/3$	....	....	.....	299,712	2
II	.00040	.00043	.00072	465	299,730	4
III	.00051	.00032	.00072	465	299,730	4
IV	.00052	.00030	.00072	462	299,727	5
V	.00052	.00031	.00072	465	299,730	5
VI	.00055	.00031	.00072	474	299,739	5
VII	.00001	.00078	.00072	453	299.718	2
VIII	.00054	.00027	.00073	462	299,727	2
IX	.00056	.000315	.000736	483	299,748	3
X	.00052	.00027	.00074	459	299,724	3
XI	0.00054	0.00023	0.00074	453	299,718	3
Weighted mean	....	....	....	.....	299,729	.....
Correction	....	....	....	.....	+67	.....
Velocity *in vacuo*	....	....	....	.....	299,796	.....

Table VII gives the results obtained with the steel octagon.

TABLE VII

	a	*b*	*c*	*VS*	*V*	Wt.
I	0.00027	0.00057	0.00071	465	299,730	3
II	.00032	.00049	.00071	456	299,721	3
III	.00059	.00028	.00069	468	299,733	3
IV	.00057	.00025	.00069	453	299,718	5
{ V_{I}	.00008	.00072	.00072	456	299,712 }	
{ V_{II}	.00054	.00030	.00072	468	299,733 }	.....
{ V_{III}	.00076	.00005	.00072	459	299,724 }	
V	Mean of 3	....	....	.....	299,723	3
{ VI_{I}	.00065	.00027	.00072	492	299,757 }	3
{ VI_{II}	.00081	.00005	.00072	474	299,739 }	.....
VI	$(2\times VI_{II}+VI_{I})/3$	....	....	.....	299,744	3
VII	.00035	.00049	.00072	468	299,733	3
VIII	.00059	.00024	.00072	465	299,730	5
IX	.00055	.00026	.00072	459	299,724	5
X	.00056	.00025	.00072	459	299,724	5
XI	0.00058	0.00025	0.00072	465	299,730	5
Weighted mean	....	....	....	.....	299,728	.....
Correction	....	....	....	.....	+67	.....
Velocity *in vacuo*	....	....	....	.....	299,795	.....

These results are collected in Table VIII.

TABLE VIII

Mirror	Year	N	n	V	Wt.
Glass 8	1925	528	150	299,802	1
Glass 8	1925	528	200	299,756	1
Glass 8	1926	528	216	299,813	3
Steel 8	1926	528	195	299,795	5
Glass 12	1926	352	270	299,796	3
Steel 12	1926	352	218	299,796	5
Glass 16	1926	264	270	299,803	5
Glass 16	1926	264	234	299,789	5
Weighted mean	....	....	....	299,796±4	....

When grouped in series of observations with the five mirrors the results show a much more striking agreement, as follows:

Glass 8	299,797
Steel 8	299,795
Glass 12	299,796
Steel 12	299,796
Glass 16	299,796

The ready success of the measurements at the distance of twenty-two miles, the majority of which were made under conditions not the most favorable (haze and smoke from forest fires; imperfections of surfaces of the revolving mirrors), would seem to indicate the feasibility of a measurement at a considerably greater distance. A convenient location for the distant mirror (diameter, 40 in.) was found at Mount San Jacinto, eighty-two miles distant. In a preliminary trial, light was returned, but so enfeebled by smoke that measurements were quite impracticable.

It is hoped that during the winter season the rains will clear the atmosphere sufficiently for accurate measurement, and accordingly work will begin again toward the end of December, 1926.

I take this opportunity to express my appreciation of the generous gift of $10,000 by Mr. Martin A. Ryerson which made this investigation possible.

APPENDIX I

Measurement of the length $2D$ of the light-path.

The light-path as shown in Figure 1 is from the surface a of the revolving mirror to $b\ c\ D\ E\ f\ E\ D\ c\ b_1\ a_1$.

The measurements of the separate elements are as follows:

Distance between bench marks $B\ B_1$, as furnished by U.S. Coast and Geodetic Survey, 35,385.5

	Meters
$BD=$	11.57
$Dc=$	8.00
$bc=b_1c=$	0.40
$ab=$	0.34
$B_1f=$	0.11
$fE=$	9.30

The D of the formula will be

$$D=ab+bc+cD+DB_1+B_1f+2fE=35,424.5M\ .$$

APPENDIX II (JULY 1)

Comparison between C.G.S. pendulum[1] and standard observatory clock:

Period of Coincidences	Temperature
23^m46^s	24°0
23 44	24.1
23 24	24.1
23 40	24.2
24 00	24.4
1423	

N = number of (double) swings per second = 1.00070 at 24°2.

Another comparison gave 1.00074 at 17°.

Whence the temperature correction is $-$.0000055 per degree.

The clock gains one second per day by comparison with time signals from Washington; giving

$$T=1.00075 \text{ at } 17^\circ\ .$$

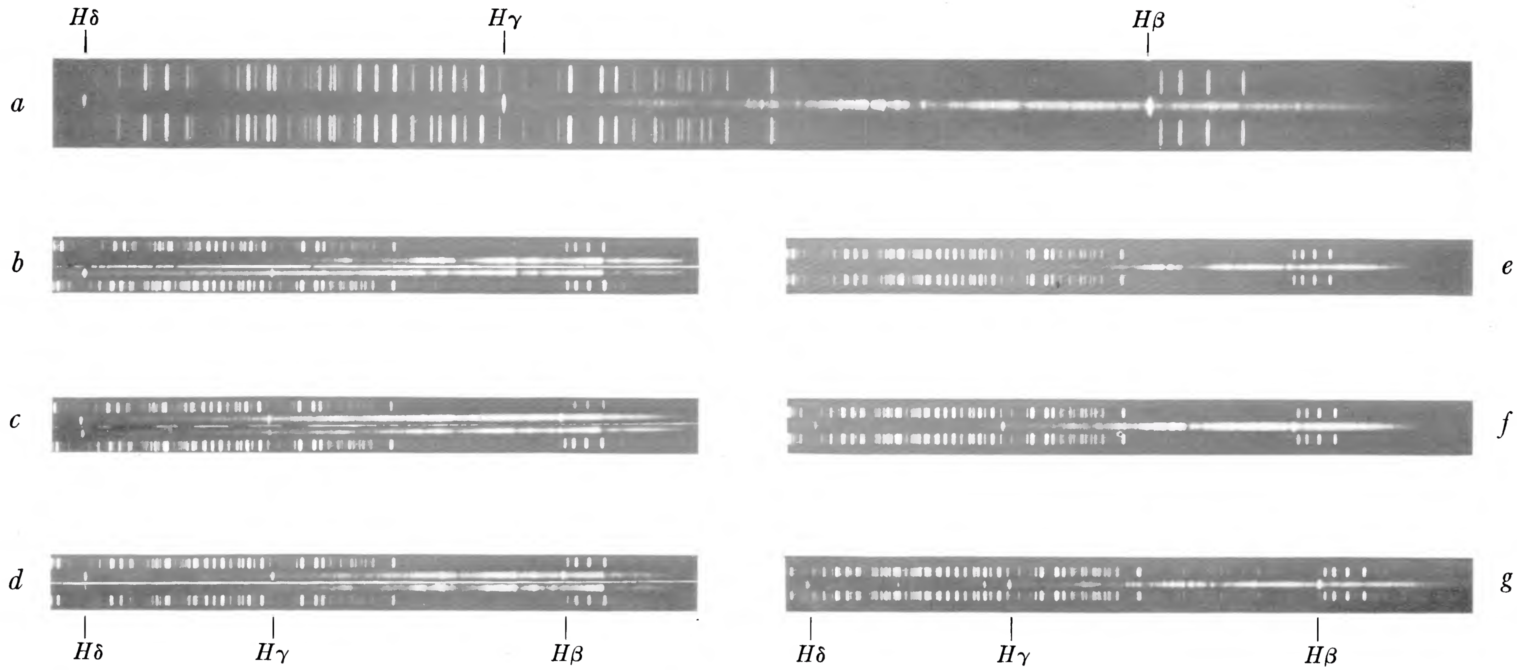
Another comparison taken August 13 gave the following results:

Period of Coincidences	Temperature
22^m41^s	19°0
23 15	19.2
23 07	19.4
22 58	19.7
22 50	20.1
23 48	21.0
23 20	21.5

Giving N = 1.00072 at 19.9°.

[1] The pendulum case was evacuated to a residual pressure of about 1 cm, for which the pressure correction is inappreciable. The amplitude correction was also negligible.

PLATE I



Spectra of S-Type Variable Stars

a) R Cygni, γ 11117; mag. 8.0; phase +32 days.
b) Upper, AA Cygni, C3377; lower, RS Ursae Majoris, C3241, April 9, 1925; spectral class M5e.
c) U Cassiopeiae: upper, C3074; mag. 7.4; phase −11 days: lower, C3538; mag. 9.0; phase +22 days.
d) T Geminorum: upper, C3240; mag. 8.9; phase −10 days: lower, C 3186; mag. 9.4; phase −47 days.
e) R Cygni, C3492; mag. 9.6; phase −61 days.
f) R Cygni, C3572; mag. 6.8; phase − 3 days.
g) R Cygni, C1055; mag. 9.7; phase +115 days.