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OBSERVATIONAL BASIS OF GENERAL RELATIVITY

By Charles E. St. John

Introduction.—The theory of special relativity was based upon the accepted null result of the Michelson-Morley experiment. Einstein drew from his general theory three quantitative tests: namely, the hitherto unexplained advance of the perihelion of *Mercury,* the deflection of light by gravitation, and the red-shift of spectrum lines in the gravitational field of the Sun. Much interest in the lay and scientific minds centers in the outcome of these tests. Their confirmation brings fundamental changes in our conceptions of the properties of space and time and hence in our outlook on the nature of the universe.

I. *The Michelson-Morley experiment.* — Historically the Michelson-Morley experiment was devised to detect the orbital motion of the Earth through the ether. The negative result originally reported has been confirmed in all repetitions of the experiment. That is, no effect due to the 30-kilometers-per-second velocity of the Earth in its orbit is observable.

A postulate in Einstein's special theory of relativity is that no observation made upon the Earth can detect its motion of translation. Observation of such a motion, however small, would undermine this fundamental postulate. The Michelson-Morley experiment is admitted to be suitable for detecting a relative motion of the Earth and the ether, if it is accessible to observation.

a) Professor D. C. Miller[1] has made extensive series of observations from which he deduces an ether drift of 10 kilo-

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[1] *Science,* 63, 433–443, 1926; *Mt. Wilson Contr. No. 373; Ap. J.,* 68, 341–402, 1928.

meters per second, and this he interprets as due not to the Earth's orbital motion but to a small fraction of a far higher velocity found for the solar system when the distant star clusters are used as a frame of reference. It is postulated that in some unexplained way the Sun's constant velocity of 200 kilometers per second or more with respect to the ether is reduced in the interferometer to 10 kilometers per second. The apex of the postulated motion is $\alpha = 17^h\ 30^m$ and $\delta = 68°$. At sidereal time $5^h\ 30^m$ the apex is at lower culmination and the projection of the assumed motion in the plane of the apparatus is a maximum. In the latitude of Pasadena this component is 98 per cent. Twelve hours earlier or later it is about one-half as large.

b) The Mount Wilson observations by Michelson, Pease, and Pearson[2] were made at the sidereal times of Miller's maximum, at 12 hours before or after maximum, and at midpoints. Increased precision was obtained by arranging for the observer to make the micrometric settings on the interference fringes from a fixed position (Fig. 1) such that he was free from the exacting conditions described by Professor Miller, who says:

> I think I am not egotistical, but am merely stating a fact, when it is remarked that the ether-drift observations are the most trying and fatiguing, as regards physical, mental, and nervous strain, of any scientific work with which I am acquainted.

For the three longer series the interferometer was set up in a well-protected basement chamber. Temperature and pressure changes with the consequent wandering of the fringes were then effectively eliminated.

A set of readings consists of ten revolutions of the apparatus —five east, five west—giving twenty determinations. The average values for a set are taken as an observational unit.

On the assumption of an ether-drift of 10 kilometers per second the differences between the series taken at the maximum and 12 hours earlier or later should be periodic, with an amplitude of 0.021 fringe for the first series, 0.035 for the second

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[2] *Proceedings of the Michelson Meeting, Optical Society of America,* October–November, 1928. F. G. Pease, *Publ. A.S.P.,* **42,** 197, 1930.

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and third, and 0.000 for the neutral series. The object of the observations by Michelson, Pease, and Pearson was to test this deduction by a purely differential method. The actual differences for the adjacent series are given in Table I (p. 280). The combinations of series are shown in the first column; the orientations of the interferometer in the second, third, fourth, and fifth; the probable error of the differences between adjacent series in the sixth; the length of path in the seventh, and the amplitude to be expected according to Miller in the last column. The differences show no evident periodicity and are not of the order of magnitude to be expected for an ether-drift of 10 kilometers per second, but only of the order of the probable errors. In the graph (Fig. 2, p. 280) of the weighted differences, the broken curve shows the observed means for series I, II, and

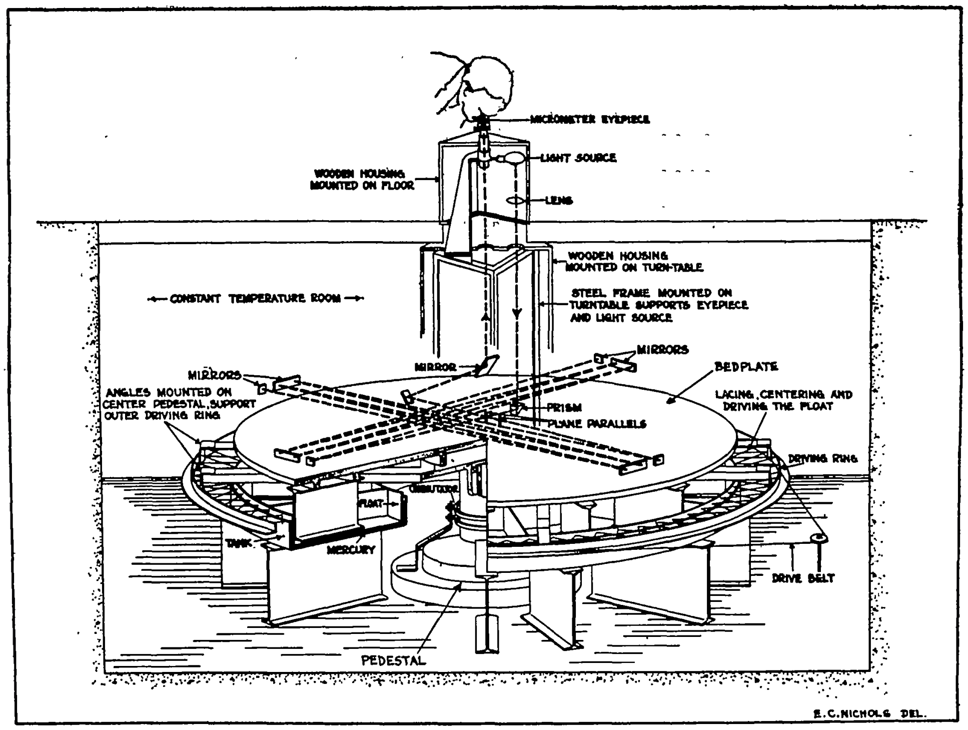

FIG. 1.—The Mount Wilson Interferometer has a float and mercury trough of iron. The surfaces and radii are machined to 0.001 inch. The instrument is accurately centered and driven by a small motor. The observer is at rest.

III, while the unbroken curve indicates the amplitude to be expected for an assumed ether-drift of 10 kilometers per second.

TABLE I

Differences in Series

Unit = 0.001 Fringe

Combination	N–S	NE–SW	E–W	SE–NW	P.E. of Difference	Path	Amplitude according to Miller
Max. I–Min. I	+0.7	+4.2	–1.4	+4.1	±2.4	55 ft.	21
Max. II–Min. II	0	+1.2	–0.1	+0.6	1.1	85	35
Max. III–Min. III	0	+2.6	+1.3	–1.7	1.4	85	35
Neu. I–Neu. II	0	–1.4	–3.0	+3.5	±1.4	85	0

As the Earth rotates on its axis, the azimuth of the maximum amplitude of the component in the plane of the interferometer should oscillate equally to the east and to the west of the meridian. As observed by Professor Miller, however, the azimuth was never east, but oscillated about a point approximately 60° west of north. This curious result has never been

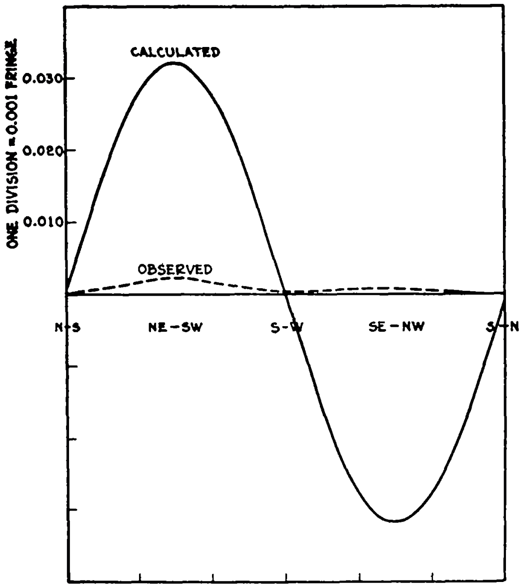

Fig. 2.—The dotted curve shows the observed maxima *minus* minima during rotation. The continuous curve is that calculated for an assumed ether-drift of 10 kilometers per second.

explained. If real, the orientation SE–NW should be the favored one in this series for detecting the differences between maximum and minimum, but at this orientation the observed amplitude of the difference between maximum and minimum is of the wrong sign, although practically zero. With an instrument as sensitive as the Michelson-Morley interferometer, small more or less periodic effects are to be expected when it is rotated, and apparently only such were found by Michelson, Pease, and Pearson. This result is confirmed by the neutral series, for which the differences should be zero.

c) At the California Institute of Technology Dr. Roy J. Kennedy has repeated the Michelson-Morley experiment with a refined modification of the original apparatus. This modification so reduces the size of the apparatus that it can be conveniently sealed in a case filled with helium at atmospheric pressure. Under these conditions any wavering of the interference fringes is imperceptible. The high sensitivity necessary because of the short path is obtained chiefly by raising one-half of the surface of the mirror a small fraction of a wave-length above the other. Two series of observations have been carried out, the first by Kennedy,[3] the second by Illingworth.[4] In both series the effect of ether-drift was practically null, there being no definitely measurable shift of the fringes depending on the orientation of the apparatus. An ether-drift of 10 kilometers per second would have produced an effect ten times the least detectable value.

d) For the repetition made at Jena under the direction of Professor Georg Joos,[5] the facilities of the Zeiss shops were available for the construction of the apparatus. The aim was to use a relatively long light-path and to obtain by continuous photographic registration permanent records measurable with the highest precision.

The moving system of four horizontal cylinders (Plate II, *b*), with extensions above for admitting the light-beam and

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[3] *Conference on the Michelson-Morley Experiment, Mt. Wilson Contr. No. 373; Ap. J.*, **68**, 341–402, 1928.

[4] *Phys. Rev.*, **30**, 692–696, 1927.

[5] Georg Joos, *Ann. d. Phys.*, **7**, 25, 1930.

below for carrying the camera, was of air-tight construction which reduced disturbances of the inclosed air to a minimum. A cross of fused quartz carried the optical system and was supported by a frame suspended within the closed cylindrical arms by a very great number of finely coiled springs.

Ball bearings replaced the mercury flotation with its difficult problems of centering. The axis of rotation could be adjusted within 1″ of the vertical. The driving was by motor through a string belt. The period of rotation was ten minutes, the motion being unbroken during a series of observations.

The apparatus was installed in a basement room of the Zeiss Works and used for the definitive observations only during intermission of work from Saturday to Sunday noons, when temperature conditions were also best.

The photographic records of the interference pattern were photometered and measured, with the result that any ether-wind effect must be less than $\frac{1}{1000}$ fringe or 1.5 kilometers per second. A similar accuracy would mean that in measuring a length equal to the distance between the Earth and Moon an error of 1 centimeter would be detectable.

Confirming the negative results found by the Mount Wilson, Jena, and California Institute observers are the balloon and Rigi observations of Piccard and Stahel,[6] and the negative outcome of the repetitions of the Troughton-Noble experiment by Tomaschek[7] and Chase.[8]

II. *The advance of the perihelion of Mercury.*—Under the Newtonian gravitational influence of the Sun, the planets describe elliptical orbits modified slightly by the gravitational perturbations caused by the neighboring members of the Sun's family. One result of the perturbations is the slow advance of the perihelia, greatest in the case of *Mercury.* The effect depends upon the mass, position, and distance of the disturbing body. *Venus,* being nearest to *Mercury,* produces more than half the total effect, while the greater mass of *Jupiter* partially

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[6] A. Piccard and E. Stahel, *Nature,* **14**, 935, 1926; **16**, 25, 1928.

[7] R. Tomaschek, *Ann. d. Phys.,* **78**, 743, 1925; **80**, 509, 1926.

[8] C. T. Chase, *Phys. Rev.,* **30**, 516, 1930.

compensates for the greater distance and produces the next largest result. Long before the days of Einsteinian relativity, the advance of *Mercury*'s perihelion, calculated from the Newtonian law of gravitation and compared with the observed advance, showed a discrepancy of about 43″ per century. This long outstanding failure of Newtonian gravitation to account for the total perihelion advance received no adequate explanation until the development of the theory of general relativity.

Sir Frank Dyson[9] in a lecture at the Royal Institution reviewed the various attempts to explain the discordance in the position of *Mercury*'s perihelion and gave grounds for dismissing all except Einstein's theory, which, however, was not devised for the purpose of explaining the discordance. The explanation came as a by-product of the general theory. A similar discussion was given by A. C. D. Crommelin.[10]

The close agreement of the long-accepted value of the discordance between observation and planetary theory with the advance in perihelion deduced from the theory of general relativity, while giving confidence to relativists, raised questions in the minds of others, particularly as to the certainty of the value determined from the observations by Newcomb upon which the discordance of 43″ mainly depends. Among others may be mentioned E. Grossman[11] who found the discordance to be 29″ or 38″, and H. R. Morgan[12] who obtained from adjustment with more recent observations values of 49″.8 and 50″.9.

That the uncertainty does not lie in the calculation of the advance according to Newtonian theory is evident from Table II (p. 284) in which the motion of *Mercury's* perihelion due to each planet found by Le Verrier, Newcomb, and Doolittle has been adjusted by J. Chazy[13] to a homogeneous system of masses and a uniform definition of the longitude of perihelion.

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[9] *Jour. B.A.A.*, 30, 136, 1920.

[10] *Jour. B.A.A.*, 30, 123, 1920.

[11] E. Grossman, *Zeit. f. Phys.*, 5, 280, 1921.

[12] H. R. Morgan, *Jour. Opt. Soc. Amer.*, 20, 225, 1930.

[13] J. Chazy, *Comptes Rendus*, 182, 1134, 1926.

TABLE II

THE ADVANCE OF THE PERIHELION OF MERCURY ACCORDING TO NEWTONIAN THEORY

Due to	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Total per Century
a ...	+276″.41	+90″.09	+2″.47	+152″.98	+7″.26	+0″.15	+0″.04	529″.40
b ...	+276.29	+90.03	+2.48	+152.98	+7.26	+0.14	+0.04	529.22
c ...	+276.28	+90.04	+2.47	+152.98	+7.26	+0.14	+0.04	529.21

a, Le Verrier 1859; *b,* Newcomb 1886; *c,* Doolittle 1912.

Observed		Calculated				
572″.70	—	529″.21	=	43″.49	=	Discrepancy by Newtonian law.

From general relativity the advance =

$$2\,r^3 \frac{a^2}{T^2c^2(1-e^2)} = 42''.9 \text{ per century}$$

r = mean distance from the Sun.
a = semi-major axis of orbit.
T = period.
c = velocity of light.
e = eccentricity of the orbit.

III. *Deflection of light in the Sun's gravitational field.*—This phenomenon was observed for the first time by the English observers in 1919,[14] again in 1922 by the American,[15] Canadian,[16] and English[17] expeditions, and in 1929 by the German expedition from the Einstein Stiftung.[18] In view of the difficulties attendant upon first observations, the results for 1919 and 1922 are in satisfactory agreement with the predictions of general relativity theory, viz. 1″.75, while the value 2″.24 found by

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[14] F. W. Dyson, A. S. Eddington, C. R. Davidson, *Mem. R.A.S.,* **62,** Appendix, 1920.

[15] W. W. Campbell and R. J. Trumpler, *Lick Obs. Bull.,* **11,** 41, 1923; *Lick Obs. Bull.,* **13,** 130, 1928.

[16] R. K. Young, *Jour. R.A.S.C.,* 17, 129, 1923.

[17] G. F. Dodwell and C. R. Davidson, *Observatory,* **84,** 130, 1924.

[18] E. Freundlich, H. von Klüber, and A. von Brunn, *Abh. d. Pruss. Akad. d. Wissensch. phys.-math. Kl.,* No. 1, 1931. *Zeit. f. Astrophys.,* **3,** 171, 1931.

Freundlich, von Klüber, and von Brunn from the 1929 observations is 28 per cent in excess of the theoretical prediction.

The Potsdam observers set out to obtain the absolute values of the star displacements by determining the scale and other plate corrections from photographic copies of a reseau impressed upon each plate of the eclipse and comparison fields photographed by the twin cameras at the time of the eclipse and a half-year later. A collimating telescope with an illuminated reseau at its focus was so adjusted that the parallel beam was reflected from the coelostat mirror into the eclipse and field cameras in directions coinciding as nearly as possible with the light beams from the eclipse and comparison fields. Dr. Trumpler[19] subjects this procedure to criticism, mainly on the ground that temperature differences between the day and night exposures rendered unreliable the determination of the plate scale from the reseau images. He made a new reduction of the Potsdam measures in which he determined the scale and other plate corrections from the star observations themselves, a procedure similar to that employed in reducing the 1919 and 1922 observations, and found a value of $1''.75$ in agreement with the relativity theory, as well as in good accord with the previous observations.

The Potsdam[20] observers do not accept the criticism of their absolute method and suggest that the agreement of the result of the new reduction with the theoretical value is not necessarily evidence of its correctness. They reserve an exhaustive consideration of the criticisms until the reduction of the observations made at the same eclipse with the 3.4-meter astrographic equipment is completed. The method of determining the scale will be free from any suspicion attaching to the reseau images impressed by the collimating telescope as the telescope was swung from one field to the other during the eclipse.

Jackson[21] has discussed briefly the Potsdam results and finds that if the residuals are solved for scale, as well as for the Ein-

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[19] R. J. Trumpler, *Zeit. f. Astrophys.*, **4**, Heft 3, 208, 1932.

[20] E. Freundlich, H. von Klüber, and A. von Brunn, *Zeit. f. Astrophys.*, **4**, Heft 3, 221, 1932.

[21] J. Jackson, *Observatory*, **54**, 292, 1931.

stein term proportional to $1/r$, the value of E becomes 1″98 instead of 2″24 but with an increase of 40 per cent in the probable error. Any systematic error arising from the determination of the scale by means of the second telescope and the collimator is eliminated.

The results to date, including Trumpler's new reduction of the Potsdam measures and Jackson's discussion of the residuals, are given in Table III.

TABLE III

OBSERVED LIGHT DEFLECTION AT THE SUN'S LIMB

Date	Station	Focus	No. of Plates	No. of Stars	Observed Deflection	Observers
1919						
May 29 ..	Sobral	19 ft.	7	7	1.98 ±0.12 pe	Dyson Davidson Eddington
	Sobral	11	16*	6–12	(0.86)± .1 pe	
	Principe	11	2	5	1.61 ± .3 pe	
1922						
Sept. 21 ..	Wallal	10	2	18	1.74 ± .3 pe	Chant Young
	Wallal	15	4	62–85	1.72 ± .11 pe	Campbell Trumpler
		5	6	134–143	1.82 ± .15 pe	
	Cordillo-Downs	5	2	14	1.77 ± .3 pe	Dodwell Davidson
1929						
May 9 ..	Takengon	28 ft.	4	17–18	2.24 ± .10 me	Freundlich von Klüber von Brunn
					1.75 ± .13 pe	Trumpler's reduction of Potsdam Measures
					1.98 ± .14 me	Jackson's solution of residuals for scale

* Poor focus caused by distortion of the mirrors.

It has been suggested that owing to the fall of temperature of the air in the shadow cone there might be, after the ordinary corrections have been made, a residual of refraction sufficient to account, either partially or completely, for the observed deflection of 1″.75. A deflection due to refraction would affect the measured diameter of the Moon observed during a total eclipse of the Sun. The matter was investigated at the eclipse of 1926 by Miller and Marriott,[22] who concluded that a reasonably accurate diameter of the Moon can be obtained by this method. With a telescope of 63 feet focus, the scale of the plates was such that the effect of the double Einstein deflection on the Moon's diameter would have been 0.325 millimeters. The measures were made by approaching tangency from the black (on the negative) corona, four settings; then by approaching from the clear glass, four settings, at 37 favorably distributed diameters, an average of 9 diameters per plate. No systematic differences were found between the two methods. The measured diameter was 2030″.16 ± 0″.18; the calculated, 2030″.20. Thus no measurable effect was found which accounts even in part for the deflection of light from stars apparently near the limb of the Sun at the time of a total solar eclipse.

IV. *Red shift of the Fraunhofer lines.*—In the case of the Sun the magnitude of the gravitational displacement of Fraunhofer lines is small, but the measurements are so precise that secondary effects due to conditions in the Sun's atmosphere must be considered. These circumstances render the investigation long and difficult.[23] Consideration of the comparative structure of the solar and terrestrial atmospheres reveals some conditions that vary with level. Several methods of sounding the solar atmosphere that yield consistent results are available: eclipse spectra, outflow from spots, ionization, and, perhaps most obvious of all to the layman, one based upon the winds prevailing in the solar atmosphere. As these winds are constant in direction but have different speeds they must be at different levels. For example, spectroscopic observations of the rotation of the Sun reveal prevailing east winds with velocities increasing with the height above the photosphere. Figure 3 shows

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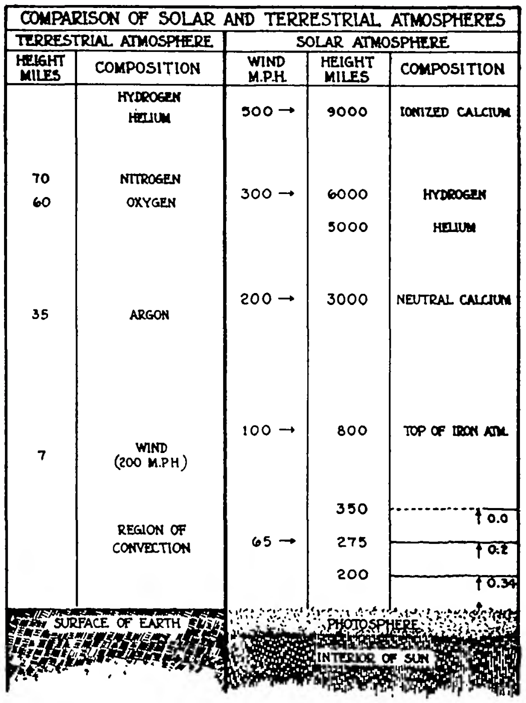
[22] J. A. Miller and R. W. Marriott, *A.J.*, **38**, 101, 1928.

[23] Charles E. St. John, *Mt. Wilson Contr. No. 348; Ap. J.*, **67**, 195–239, 1928.

striking similarity in the distribution of the constituents of the terrestrial and solar atmospheres. In sounding the atmosphere of the Earth from above, hydrogen and helium are first encountered, then nitrogen, oxygen, and argon are added in increasing proportions until below seven miles all the atmospheric constituents are present; similarly for the Sun, ionized calcium is first met, then, in increasing measure, hydrogen, helium, neutral calcium and iron, until near the photosphere all elements detected in the Sun are found. The lower region of the Earth's atmosphere is characterized by convection currents; so also is the solar atmosphere near its base. At higher levels there is, however, an important difference. In the Earth's atmosphere,



COMPARISON OF SOLAR AND TERRESTRIAL ATMOSPHERES

TERRESTRIAL ATMOSPHERE		SOLAR ATMOSPHERE		
HEIGHT MILES	COMPOSITION	WIND M.P.H.	HEIGHT MILES	COMPOSITION
	HYDROGEN HELIUM	500 →	9000	IONIZED CALCIUM
70 60	NITROGEN OXYGEN	300 →	6000 5000	HYDROGEN HELIUM
35	ARGON	200 →	3000	NEUTRAL CALCIUM
7	WIND (200 M.P.H)	100 →	800	TOP OF IRON ATM.
	REGION OF CONVECTION	65 →	350 275 200	0.0 0.2 0.34

FIG. 3.—Similarities and differences in the distribution of elements in the terrestrial and solar atmospheres. Both atmospheres show convection currents at low levels, but in the terrestrial atmosphere the lightest element is highest, while in the solar atmosphere the heavy ionized calcium atoms extend to a higher level than those of the lighter permanent gases, being supported against gravitation by the greater pressure of radiation due to the great absorption of energy by atoms producing the H and K lines.

above seven miles, the respective gases are distributed according to their molecular weights,[24] the lightest at the top, while in the solar atmosphere the ordinary gas laws hold only near the photosphere, the upper layers being supported by radiation pressure with heavy calcium above the lightest gases. With this difference in solar conditions at low and high levels go corresponding differences in the behavior of Fraunhofer lines originating at different levels. The lower and upper regions of the Sun's atmosphere require therefore separate consideration.

a) For low-level lines, observations at the center of the Sun's disk give displacements, λ center — λ vacuum, which are smaller than those calculated from relativity theory, a discrepancy between prediction and observation that requires consideration.

The wave-lengths of the lines at the limb are longer than at the center, the so-called limb effect.[25] There are theoretical and observational grounds for the conception of convection currents. On the assumption that the shorter wave-lengths at the center are due to an upward convection current, its effective upward velocity may be deduced from the observations. Its value is found to be greatest at low levels, dying out at approximately 350 miles above the photosphere. For example, in the spectral region λ 6135 and for lines reaching 200 miles above the photosphere, the displacement, λ limb — λ vacuum, is +0.014 A; the displacement, λ center — λ vacuum, is +0.007 A, a decrease of 0.007 A at the center, which, considered as a Doppler effect, gives at the center of the Sun an upward velocity of 0.34 kilometers per second. This is illustrated in columns 3, 4, and 5 of Figure 4 (p. 290), which reproduces the solar half of Figure 3, together with the observed and calculated red-displacement of lines at different levels. The corresponding part of column 6 gives the calculated relativity displacements. On determining the upward velocities corresponding to the differences, observed minus calculated, for these low-level lines, they are found to be the same, within the errors of measurement, as those derived from the differences center minus limb, i.e., both the so-called

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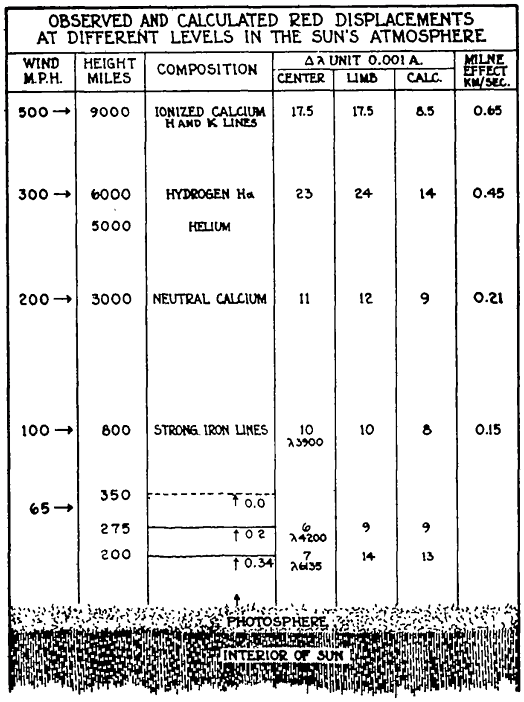
[24] W. J. Humphreys, *Physics of the Air*, 1920, pp. 68–70.

[25] *Loc. cit., Ap. J.*, 67, 226–230, 1928.

limb effect and the discrepancy between the observed and calculated red-displacement for these lines are results of upward radial velocities of the same order of magnitude.



OBSERVED AND CALCULATED RED DISPLACEMENTS AT DIFFERENT LEVELS IN THE SUN'S ATMOSPHERE

WIND M.P.H.	HEIGHT MILES	COMPOSITION	Δλ UNIT 0.001 A.			MILNE EFFECT KM/SEC.
			CENTER	LIMB	CALC.	
500 →	9000	IONIZED CALCIUM H AND K LINES	17.5	17.5	8.5	0.65
300 →	6000	HYDROGEN Hα	23	24	14	0.45
	5000	HELIUM				
200 →	3000	NEUTRAL CALCIUM	11	12	9	0.21
100 →	800	STRONG IRON LINES	10 λ3900	10	8	0.15
65 →	350	↑ 0.0				
	275	↑ 0.2	6 λ4200	9	9	
	200	↑ 0.34	7 λ6135	14	13	

FIG. 4.—Observed *minus* calculated red displacement. The deficit at the center in the case of low-level lines is due to the greater velocity of the gases rising over hot areas relative to the velocity of gases falling over the larger and cooler dark areas. The deficit disappears with the vanishing of the vertical component at the limb where the observed and calculated red displacements agree.

The excess for high-level lines when reduced according to wave-length is greatest at the highest level, simulating a velocity of recession which is the same at the center and limb and accounts for excess observed *minus* calculated in the case of high-level lines—the Milne effect.

The bright granulations of the photospheric surface are best explained as convection phenomena,[26] i.e., as the peaks of columns of hot gases rising over limited bright areas and descending over the less bright but larger interspaces, which Langley estimated as some five-fold larger than the bright areas. The masses of the up-and-down transfers being equal, the relative velocities are inversely as the areas. The spectroscope

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[26] A. Unsöld, *Zeit. f. Astrophys.*, **1**, 138, 1932.

integrates over many such regions and gives a small violet displacement due to the higher velocity of the rising material. Figure 5 showing an old convection experiment illustrates this, as does also the higher stream velocity in a narrow river channel compared with that in the broader reaches above and below.

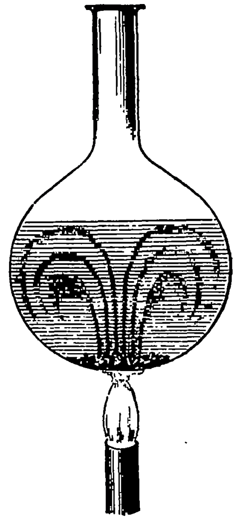

FIG. 5.—Illustration of a rising column in a fluid receiving heat over a small area and the slower falling of the outer cooler parts having a larger cross-section.

b) At high levels where radiation pressure dominates and where about one per cent of the Fraunhofer lines originate the conditions are very different. Typical is the behavior of the very strong iron lines, λ 4227 of calcium, the D lines, the green magnesium triplet, Hα and the H and K lines of ionized calcium. These lines have the same wave-lengths at limb and center, in all cases longer than calculated from relativity theory. As the same excess of red-displacement obtains at the center and at the limb of the Sun, a common cause is indicated. At high levels the support of the solar atmosphere is by radiation pressure. Milne and Merfield have shown that the greater momentum $h\nu$, gained by absorbing centers in the violet half of a strong absorption line, results in the expulsion from the Sun's atmosphere of a larger number of atoms absorbing from the violet side of an absorption line than of atoms absorbing from the red side. After emission some of the atoms absorbing from the violet wing will possess large outward velocities and hence the next absorption will be from the violet side of the absorption line where the radiation is stronger than at the center; consecutive absorptions and emissions will therefore endow these atoms with an increasing outward acceleration and some of them will eventually escape from the Sun with enormous velocities. When the Fraunhofer spectrum is observed there are, then, more atoms absorbing from the red half than from the violet half of the line and the absorption line will appear displaced toward the red. The effect becomes more pronounced with increasing height and is the same at limb and center.

High-level lines should then show a larger displacement to the red than calculated from relativity theory. The excess red-displacements for high-level lines when referred to the corresponding wave-lengths simulate the downward velocities given in column 6 of Figure 4. These displacements may be considered to measure the Milne effect and to account for the excess red shift shown by high-level lines.

c) The system of *Sirius* offers a unique opportunity for observing the gravitational displacement of spectral lines on an extraordinary scale. The elements of this double-star system are well determined. The companion has been followed through more than a revolution, which it completes in a period of 50 years. Its mass is approximately 0.85 the mass of the Sun, and its radius determined from the established relation between brightness per unit area and total brightness[27] is 0.028 the radius of the Sun. The Einsteinian displacement is proportional to M/R. For the Sun this ratio is equivalent to a recessional velocity of 0.635 kilometers per second. For the companion of *Sirius* it becomes $0.85 \times 0.635/0.028$ or 19 kilometers per second, thirty-fold that for the Sun. The brightness of the two stars is in the ratio of 1 to 10,000 and their separation 10″. To obtain the spectrum of the companion as free as possible from the scattered light of *Sirius,* times of excellent seeing were selected at epochs when the separation was large, as in 1924 and 1927 (Fig. 6). The relative distri-

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[27] F. H. Seares, *Mt. Wilson Contr. No. 226; Ap. J.*, **55**, 165–234, 1922.

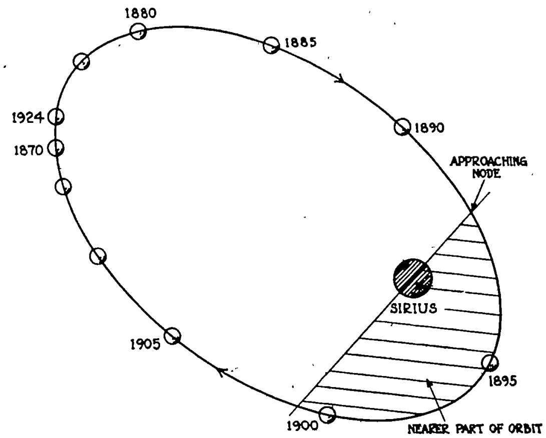

Fig. 6.—The system of *Sirius* projected on a plane perpendicular to the line of sight. The nearer part of the orbit of the companion is lined. From periastron to apastron the companion in moving clockwise recedes relative to *Sirius*. In 1924 and 1927 its relative recessional velocity was 4 and 5 kilometers per second, respectively.

bution of the light in the spectrum of the companion and of the scattered light of *Sirius* is such that the spectrum of the companion in the region of the Hβ line of hydrogen may be obtained practically free from the spectrum of *Sirius* (Fig. 7). The ob-

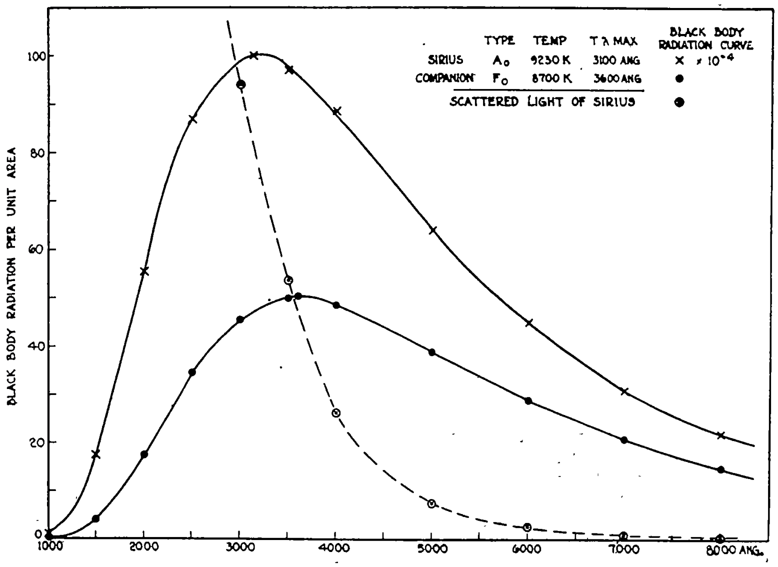

Fig. 7.—Relative intensities of the scattered light of *Sirius* and the direct light of the companion. At Hβ, 4861 A, only a very small amount of scattered light entered the slit of the spectrograph, and the spectrum of the companion was obtained practically free from it.

servations of Adams[28] based upon four spectrograms taken in 1924 are confirmed by three by Moore[29] in 1927. The gravitational displacement of the lines in the spectrum of the companion is obtained by comparing them with corresponding lines in the spectrum of *Sirius* and allowing for the relative motion of the two stars. At the epochs of observation the companion was receding relatively to *Sirius* with velocities of 4 and 5 kilometers per second, respectively. The gravitational displacement of the Sirian lines is too minute to be taken into consideration as a correction.

MEASUREMENT OF THE SPECTRUM OF THE COMPANION OF SIRIUS

		RECESSIONAL VELOCITIES		
Epoch	Observer	Measured	Relative Motion	Gravitational Red Shift
1924	Adams	+23 km/sec.	*minus* 4 km/sec. =	19 km /sec.
1927	Moore	+24 km/sec.	*minus* 5 km/sec. =	19 km/sec.

The close agreement between the two measures and of each with the calculated value is obviously accidental, but even with allowance for the estimated probable errors of 3 to 5 kilometers per second the results remain of the order of magnitude of the calculated value.[30]

For the companion of *Sirius* both the magnitude of the effect and the error of measurement are such that influences due to small disturbances and slightly varying conditions in the star's atmosphere are negligible; while for the Sun, as already stated, the gravitational effect is small and the measures so precise, as compared with measurements on stars, that effects due to conditions in the Sun's atmosphere must be taken into account.

V. *Corroborative evidence.*—The special theory of relativity is strongly supported by the work of Sommerfeld, whose masterly application of it to the fine structure of spectrum lines has been confirmed in all physical laboratories where it has been studied. It is significant, also, that the ultimate basis for the-

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[28] W. S. Adams, *Proceedings N.A.S.*, **11**, 382–387, 1925.

[29] J. H. Moore, *Publ. A.S.P.*, **40**, 229–233, 1928.

[30] Eddington, *Mon. Not.*, **84**, 1924.

ories of wave-mechanics is sought in general relativity as representing the widest of generalizations.

In this brief review of the observational results the cumulative effect of the experimental evidence gives strong support to the statement of Sir James Jeans,[31] who says: "The general theory of relativity has long passed the stage of being considered an interesting speculation . . . . and has qualified as one of the ordinary working tools of astronomy."

Carnegie Institution of Washington
Mount Wilson Observatory
July 16, 1932

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[31] Jeans, *The Universe around Us*, pp. 72–73, 1929.