

## THE MICHELSON–MORLEY–MILLER EXPERIMENTS BEFORE AND AFTER 1905

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### I. INTRODUCTION<sup>1</sup>

Special relativity theory is often asserted to have grown out of the difficulties of interpreting the “negative” results of the Michelson–Morley aether-drift experiment of 1887. This assertion is more than half true as a generalization about the sociology of physics and more than half false in the individual case of Albert Einstein’s famous paper of 1905, “On the electrodynamics of moving bodies”.<sup>2</sup>

The overlap of truth and falsity in most accounts of the origins of relativity theory may be explained in various ways, but one neglected factor in that summation is the way different canons of scholarship in physics and in history have affected the selection of data and the narration of relationships between experiment and theory. Physicists generally write the “Whig” interpretation of their history, and historians when they dare to trespass have usually given us Tory views.<sup>3</sup> This has meant that the success-story bias, introduced for justifiable pedagogical reasons in textbooks and for didactic reasons as implicit history in more advanced treatises, has overshadowed careful attention to chronology and has presumed a linear and sequential development that cannot be justified. More thorough and explicitly historical research is required to correct such oversimplifications.

Recent studies on the history of physics since Maxwell and on the development of relativity and quantum ideas have shed much new light on our perspective of the science of optics since 1880. Modern scholarship has not only cast doubt on the genetic connection between Michelson–Morley and relativity theory but also has revived interest in the social processes by which private science becomes public knowledge.<sup>4</sup> The purpose of this paper is to recount the record left by the experimental work of Albert A. Michelson, Edward W. Morley, and Dayton C. Miller with instruments called aether-drift interferometers between 1880 and 1930. Specifically, I shall attempt to narrate precisely how Michelson’s experiment was first performed, partially repeated, and finally completed by being challenged nearly half a century after its conception.

In order to appreciate the social complexity of the long life of Michelson’s aether-drift experiment, it is necessary to emphasize that the Michelson–Morley experiment could better be known as the Morley–Miller experiments during the 1900–6 period, and that during the post-war decade of the 1920s, the essential culmination of this experiment became a contest between Dayton C. Miller and Michelson. Thus, only after the celebrated experiment had come to serve as the chief pedagogical justification for relativity theory was it revived, refined and redressed by Miller and Michelson. The Michelson/Miller experiments of the twenties were a reluctant competitive effort to resuscitate the aether and, at least in Miller’s case, to determine the “absolute motion” of the Earth through space.<sup>5</sup>

## II. THE MICHELSON–MORLEY EXPERIMENTS BEFORE 1905

James Clerk Maxwell died in 1879, the same year that Albert Einstein was born and that Albert Michelson began his career of concern over the velocity and behavior of light. It is fairly well known that Maxwell himself had urged repeatedly that someone find a way to test directly for the Earth's motion in orbit either by extremely accurate measurements of the moons of Jupiter or by one-way transit comparisons of the velocity of light with and against the Earth's motion. It is not widely known, however, that Maxwell had tried a similar experiment while first working out his synthesis of electromagnetism and light back in 1864, but had been dissuaded from publishing by G. G. Stokes who was then the most distinguished and fair-minded advocate of the undulatory theory and its luminiferous aether.<sup>6</sup>

Ever since Thomas Young and Augustin Jean Fresnel had revived the wave theory of light at the beginning of the nineteenth century, the undulatory theory had been confirmed and extended until corpuscularian (i.e., Newtonian) notions of light were almost completely abandoned. Although the early analogy of sound with light had to be abandoned quickly when polarization and double refraction phenomena showed the transverse nature of light's propagation, other mechanistic analogies, especially from fluid mechanics, replaced those from acoustics. Maxwell himself combined the mechanistic ideas of Faraday with the mathematical formalism necessary to link electricity, magnetism, and light in one great synthesis.<sup>7</sup>

The hypothesis of a luminiferous aether, therefore, had grown into a doctrine, if not a dogma, by 1880. The subtle imponderable, ubiquitous light-medium was a necessary concomitant to the belief that radiant energy is transferred by waves through "empty" space. Diffraction, interference, and spectroscopic phenomena had grown so numerous and were so well explained by the wave theory that the third quarter of the nineteenth century was fairly permeated with physical speculation about the luminiferous plenum.<sup>8</sup>

In discovering and explaining astronomical aberration, James Bradley in 1729 had used a nautical analogy (a sailboat's weather vane) to understand the apparent displacement of stars due to the combination of the velocity of light with the velocity of Earth's orbital motion. Bradley's unsuccessful quest for stellar parallax eventuated in a new understanding of relative motion, a new standard of precision measurement, and new corroborative evidence for the Copernican doctrine as well as for astronomical calculations of the velocity of light.<sup>9</sup>

Histories of optics seldom credit the full complexity of the mid-century rivalry between A. H. L. Fizeau (1819–96) and J. B. L. Foucault (1819–68) in their various experimental efforts. Fizeau was first in 1849 to find a terrestrial method for measuring the velocity of light by his occulting gearwheel, and Foucault improved that value with his revolving mirror method the next year. Then both sought an *experimentum crucis* for the comparison of the velocity of light in air and in water. On May 6, 1850, both published in *Comptes rendus* their methods for deciding between the wave and particle theories, and Foucault's results unequivocally claimed to confirm the undulatory theory by showing the velocity of light to be less in water than in air.<sup>10</sup> The next year Fizeau improved Foucault's

design and results with his “aether-drag” experiment to gain quantitative support for Fresnel’s idea of an all-pervading but partially dragged aether. While Foucault was also working with heavy pendula to demonstrate the rotation of the Earth and with massive fly wheels in rapid rotation to demonstrate the gyroscopic principle, Fizeau concerned himself with the Doppler effect applied to light and the Fresnel hypothesis regarding the luminous aether.<sup>11</sup>

A growing number of other European physicists also had contributed to the problem of light in relative motion. D.F.G. Arago (1786–1853) was an early convert to the wave theory and the primary liaison between Young and Fresnel. Sir George B. Airy (1801–92), Britain’s Astronomer Royal, had in 1871–72 perfected the water-filled zenith telescope for an experiment to test the Fresnel drag coefficient by observing possible aberrational anomalies caused by the influence of Earth’s motion on the transit of light through transparent media. Other British, Dutch, Belgian, French, and German scientists had shown similar concerns, and so Maxwell’s several review articles on the problem of the relative motion of Earth and aether just before his death expressed a pessimistic challenge to the scientific community to find a way to make a second-order measurement, namely, a comparison of the squared ratio, of the velocity of Earth to the velocity of light.<sup>12</sup>

Michelson’s fresh triumph with his velocity of light determinations at the U.S. Naval Academy and with Simon Newcomb of the Nautical Almanac made him a likely candidate to take up this challenge. As a Naval Officer he saw an analogy, just as James Bradley had in explaining astronomical aberration, with computations of true wind speed and direction. If the Earth, moving through its orbit, nutating and rotating on its axis, and entrained with the motions of the solar system through intergalactic space, were like a ship moving across the sea and through the air, then it should be possible somehow to build an optical current-meter or pitometer sensitive enough to measure the second-order “Relative Motion of the Earth and the Luminiferous Aether”.<sup>13</sup>

In his 1881 paper by that name, Michelson described his hypothesis, apparatus, and null results during observations made in April from the cellar of the Potsdam Astrophysicalisches Observatorium. His original apparatus was a two-armed brass device, subsidized by Alexander Graham Bell and supervised by Hermann von Helmholtz. Michelson first called it an “interferential refractometer” after similar devices invented by Fizeau, J. Jamin, and A. Cornu. His purpose in the original experiment, as reported, was to find, not merely the orbital component of Earth’s velocity (as Michelson later erroneously emphasized), but what Miller later called the “absolute motion” of the Earth through the Universe.<sup>14</sup>

As a post-graduate student in Europe, Michelson carried recommendations from Simon Newcomb for entrée into many universities, laboratories, and observatories. But after his April experiment became known and the results became debated by Alfred Potier, another protégé of Cornu who was to become an influential French official, and H. A. Lorentz, a promising Dutch physicist, Michelson needed no introduction among opticians in Europe. He was the young American who had challenged the received theory of Fresnel on astronomical aberration by saying in conclusion:

The interpretation of these results is that there is no displacement of the interference bands. The result of the hypothesis of a stationary ether is

thus shown to be incorrect, and the necessary conclusion follows that the hypothesis is erroneous.<sup>15</sup>

Both Potier and Lorentz later showed Michelson his serious error in neglecting the effect of Earth's motion on the path of the pencil at right angles to the Earth's orbital vector. But by then Michelson was more excited about the sensitivity of his new instrument than about the validity of the experiment that had called his interferometer into being.<sup>16</sup>

Michelson met the chemist Edward Morley, who was 14 years his senior, when he returned to the U.S.A. to take up his duties as professor of physics at the new Case School of Applied Science in Cleveland. But not until after both attended the famous "Baltimore Lectures" of Sir William Thomson [later Lord Kelvin] in 1884 did their mutual respect and interests mature toward a collaborative project.<sup>17</sup> On the advice of Thomson, Lord Rayleigh, and J. Willard Gibbs, Michelson and Morley undertook to retest together the famous Fizeau "aether-drag" experiment that had become the primary evidence for Fresnel's hypothesis of a stationary aether and for his drag coefficient. This they did in 1885–86, as is so well described by R. S. Shankland in his recent article on the Michelson–Morley experiment. Their findings thoroughly corroborated both Fresnel and Fizeau, thus lending support to the hypothesis of a ubiquitous, stagnant luminiferous medium.<sup>18</sup>

In 1886, after five years of lapsed time and two years of planning, Michelson and Morley began seriously to redesign the Potsdam experiment, increasing the optical path by a large factor for a definitive "aether-drift" test. Evidently Michelson and Morley were seeking primarily the orbital component of Earth's motion and avoiding the problem of solar motion as they performed their classical experiment of 1887.

The famous plan and orthogonal diagrams of their apparatus, their descriptions of the sandstone slab floated on a mercury bearing, and their calculations of expectations from the received theory of aberration are too familiar to need reproducing here. Shankland's recent articles again suffice, up to the point where he summarizes the classical results by saying "No longer was it possible to believe that a positive result might be hidden in the errors of observation, and the doubts which had hung over Michelson's 1881 Potsdam experiment were now entirely removed by the Cleveland experiment".<sup>19</sup> This widely-shared modern consensual judgment is not only historically inaccurate but also in danger of being overthrown by recent progress in astrophysics and cosmology.<sup>20</sup>

During only four days, in July 1887, Michelson and Morley performed the simple yet surprising observations that were to immortalize them a generation later, much to their chagrin. Michelson walked the circuit and called off his estimates of fringe-shift at each of 16 equidistant compass points while Morley usually sat by and recorded data. Their entire series of observations consisted of only 36 turns of the interferometer covering a total of six hours duration spread over a five day period. They expected to find after data reduction something like a band-shift of 0.4, but at most they could report seeing only about one-twentieth of their prediction of a shifting distance between fringes.<sup>21</sup> Having neglected the motion of the solar system, the two experimenters promised to repeat their observations at intervals of three months, but never again did Michelson and Morley together repeat this experiment.

Their classic paper of 1887 is inconspicuously but significantly divided into two parts: the first nine pages describe the experiment and offer the conclusions cited above; the last four pages appear as a "Supplement", apparently appended just before the November issue of the *American journal of science* went to press. The final sentence of the first section is a subjunctive-mood critique of Stokes's and Lorentz's theories to explain why the aether seems to be at rest near Earth's surface. In first submitting their empirical findings for publication then, Michelson and Morley seem to have been overwhelmed by the mass of untested assumptions underlying the aether and undulatory theories. Nevertheless, they were not yet despondent enough to have thought it necessary to call off their projected seasonal tests. Sufficient discouragement to call a moratorium on further testing did come a short time later, however, because their "Supplement" begins by stating: "It is obvious from what has gone before that it would be hopeless to attempt to solve the question of the motion of the solar system by observations of optical phenomena *at the surface of the earth*".<sup>22</sup> They suggested, however, that repetitions at a greater height above sea level, using a glass instead of wooden cover for the optics, might yield more significant results for the relative motion of Earth and aether. Meanwhile, their disappointment was assuaged by other affairs and by a new interest in interferential metrology. Shortly thereafter, Michelson moved away to Clark University, then to Chicago; and Morley returned to quantitative volumetric analyses of air and water.<sup>23</sup>

As the concurrent work of Heinrich Hertz became known, the luminiferous aether became also the electromagnetic aether, and space was more firmly than ever identified with a plenum. Maxwell's electromagnetic continuum seemed far more decisively confirmed by Hertzian waves than the aether seemed threatened by the Michelson–Morley aether-drift test. In 1892, Oliver Lodge performed his aether-viscosity experiment, rotating two massive flywheels on either side of an optical racetrack, to see if matter might drag the neighboring aether with it when it moves. Lodge's experiment likewise gave null results, and so far as astronomical aberration was concerned, it seemed to contradict Michelson and Morley's repetition of the "aether-drag" experiment, whereas Hertz seemed to counter-balance the aether-drift experiment.<sup>24</sup>

The hypothesis that matter might contract minutely along its axis of movement through space was first advanced by G. F. FitzGerald in 1889 and again simultaneously by FitzGerald and H. A. Lorentz in 1892. This contraction hypothesis quickly gained wide notoriety as an *ad hoc* explanation for the failure of Michelson's experiment to show an aether-wind.<sup>25</sup> The general ferment in physics introduced by cathode, canal, and X-rays as well as by radioactivity and the quantum of action was leading many theoreticians to consider that the wave of the future lay with the physics of the aether.<sup>26</sup>

The discovery of X-rays by W. K. Roentgen in 1895 was accompanied by his belief that they might be the long-sought longitudinal vibrations of the aether, for example, and this belief was impressive at first. Roentgen's rays stimulated Michelson to venture an ill-starred theoretical paper proposing a modified aether-vortex explanation of X-rays.<sup>27</sup>

Shortly thereafter Michelson constructed an immense vertical interferometric pathway (in rectangular pipes 200' × 50') all around the outside north wall of the Ryerson Laboratory in Chicago. He hoped with this apparatus to detect a

difference in relative motion corresponding to a difference in elevation. His observations in March 1897 were published in June under the same title that he used in 1881 and 1887, and his report was again null to approximately the same degree. But significantly Michelson surmised that the Earth's influence upon the aether must be "extended to distances of the order of the earth's diameter". Michelson was unwilling to let the FitzGerald–Lorentz hypothesis have the field; he insisted that two other possibilities (perfect permeability and/or perfect entrainment of the aether) were at least as plausible as the contraction thesis.<sup>28</sup>

Morley also in 1897 returned to interferometric work. After parting company with Michelson, Morley had briefly considered a test of the velocity of light in a static magnetic field. Henry T. Eddy of Minneapolis had suggested this test of Hall's Effect, but by 1897 Morley's collaborator was the young physicist from Princeton, Dayton C. Miller, who had succeeded Michelson at Case. The results of this first Morley–Miller collaboration, published in 1898, were again null; they found no displacement greater than one-twentieth of a wavelength.<sup>29</sup>

While Lorentz's famous treatise, the *Versuch* of 1895, had made the Michelson–Morley experiment a central consideration in developing Lorentz's electronic theory, probably more important to inflating the claim of those 36 turns in July 1887 was the Adams prize essay of Joseph Larmor, *Aether and matter*, published in 1900.<sup>30</sup>

Also in 1900, Lord Kelvin lamented that only "two clouds" threatened the fair skies of a dynamical theory of heat and light: the first cloud was labelled the problem of the relative motion of aether and ponderable bodies, and the second was the Maxwell–Boltzmann doctrine regarding the equipartition of energy. Kelvin had been protesting almost too much, since 1884 at least, that the luminiferous aether was a very real, very rigid substance that filled an infinite universe with the electromagnetic medium required for the transverse wave propagation of light and radiant heat. In 1904 when he revised and published his 20-year-old Baltimore Lectures, Kelvin again admitted that the only serious, perhaps insuperable difficulty in the way of his mechanistic notion of motion in an infinite elastic solid was the Michelson–Morley experiment: "I cannot see", he said, "any flaw either in the idea or in the execution of this experiment."<sup>31</sup>

Nor was Kelvin alone. Henri Poincaré and Lorentz, equally revered as patriarchs of mathematical physics, likewise continued to write and speak frequently about the anomalies raised by the supposedly impeccable experiment devised by Michelson.<sup>32</sup> Oliver Lodge and Joseph Larmor, Arthur Schuster and M. G. Sagnac, William Magie and Leigh Page, Gustave LeBon and even J. J. Thomson were among the most important aether-apologists during the decade of World War I.<sup>33</sup> Most theoreticians, including the young Einstein, accepted by 1905 a received tradition that velocity of light measurements showed no significant variations under any conditions. But experimentalists continued in various ways to test for relative motion differentials that might be revealed by radiation pressure or double refraction experiments.<sup>34</sup>

Neither Michelson nor Morley took much pride or interest in the ferment growing around their aether-drift experiment.<sup>35</sup> Theoretical critiques by William M. Hicks, a student of Maxwell's, and Wilhelm Wien, however, elicited some

responses between 1902 and 1904, as Michelson reconsidered his calculations along with some new proposals, and as Morley and Miller did likewise with “the Theory of Experiments to Detect Aberrations of the Second Degree”. Michelson, however, was not concerned enough to return to the aether-drift problem for the moment, whereas Morley and Miller, who had been stimulated by Kelvin’s address and personal encouragement in 1900, tried, as time would permit between 1901 and 1906, to design an interferometer experiment that would test specifically for measurable evidence of the FitzGerald–Lorentz contraction hypothesis.<sup>36</sup>

The use of white-pine lumber as an interferometer base in 1902 proved worthless in the climate of their basement laboratory, and so with funds from the American Academy of Arts and Sciences they procured in 1904 an entirely new apparatus made of structural steel girders in the shape of an equal-arm cross. This interferometer base weighed about 1200 kilograms and required about 275 kilograms of mercury to bear it in the cast iron trough on top of the wooden float that Michelson and Morley had first used. Various combinations of optical elements, distance gauges, and testing materials were used with this apparatus during 1904–6 and again after 1921, but the effective total light path remained about 6406 centimeters, and the operation and design remained true to the classic experiment. The path length was three times longer than in 1887, and Morley and Miller confidently expected this elaborate new gear to produce some positive results. However, their objectives were confused by the state of the theory: they titled their paper of May 1905, “Report of an Experiment to detect the FitzGerald–Lorentz Effect”, but since they found no support either for the contraction hypothesis or for Hicks’s interpretation that the 1887 results were not negligibly small, they were forced to revert to the position that this was simply another more refined version of the aether-drift test on the classic model.<sup>37</sup>

Meanwhile, Lorentz had in 1904 finished and published his famous transformation equations to the second order, so that the cumulative null results from the classical Michelson–Morley experiment and from the Rayleigh, Brace, and Trouton–Noble experiments were embodied in a mathematical synthesis.<sup>38</sup> Poincaré’s and Lorentz’s work toward the principle of relativity was raised to the level of a postulate by Einstein, and Hermann Minkowski raised that postulate to the level of a recognized theory by 1908.<sup>39</sup>

In July 1905, however, Morley and Miller for the first time moved their apparatus out of its basement laboratory to a hilltop on Euclid Heights, 300 feet above the level of Lake Erie. There in a hut with eisenglass windows all around and a glass-box casing for the optical paths, they began to take systematic observations to test Stokes’s hypothesis of entrainment, the idea of a stagnant aether near sea level with aether-wind aloft analogous to our atmosphere. Temperature control, always the primary difficulty, was vexatious on the Heights, but by November 1905, they had reduced 230 turns of their “rigid” steel-girder interferometer to tabular figures. They were still testing for contraction, however, and their results on the classic assumptions of 1887 turned out to be no better than before. The experiments on Euclid Heights were abandoned before either the increase in altitude could be evaluated or seasonal tests performed.<sup>40</sup> Morley retired in 1907 (the same year that Michelson became the first American Nobel Prize winner in science), and Miller then turned all his

research attention toward the science of sound and the technology of music, especially the flute.<sup>41</sup>

Morley and Miller had by 1906 carried the aether-drift experiment far beyond the report of 1887 but not so far as they wished. They still saw an enigma in the aether, and they abandoned their work without knowing that Einstein had announced quietly that “the introduction of a ‘luminiferous aether’ will prove to be superfluous inasmuch as the view here to be developed will not require an ‘absolutely stationary space’ provided with special properties, nor [will it] assign a velocity-vector to a point of the empty space in which electromagnetic processes take place”.<sup>42</sup> Thus, by ignoring the aether concept and its correlative assumption of absolute space, Einstein asserted the aether to be *überflüssig* and solved the drift problem by making it meaningless. But the development of that consensus among physicists took place over the next 25 years.

### III. THE MILLER/MICHELSON EXPERIMENTS AFTER 1905

In June 1905 Einstein, with his paper on the photoelectric effect, effectively revived the corpuscular theory of radiant energy transfer and, by supporting Planck’s quantum ideas, also revived the view that light has a granular structure. With his paper on Brownian motion in July 1905, Einstein began a new chapter in molecular physics, that reinvigorated the kinetic theory of heat. And finally in September of the same year, he published his paper “On the Electrodynamics of Moving Bodies”, which raised the principle of relativity into a postulate and recognized the speed of light as a new absolute limit, equivalent, as he said, to playing “the part, physically, of an infinitely great velocity”.<sup>43</sup>

It is no wonder, then, that we consider 1905 the *annus mirabilis* of Albert Einstein’s contributions to twentieth-century physics. These three papers, preceded and followed by many other contributions, were to become recognized, at least by the time of the first Solvay conference in 1911, as theoretical contributions of the first magnitude toward a fresh understanding of how nature behaves. In the last of those three papers, Einstein’s critique of the basic ideas of space and time or length and simultaneity provided a dramatic challenge to long-standing presumptions of ‘classical’ physicists regarding invariance, basic reference frames, co-ordinate transformations, and notions about compound velocities. All this success seen in retrospect is so dazzling that few scholars have found it worthwhile to study the way in which relativity theory became accepted and acceptable to the scientific community.<sup>44</sup>

The success-story bias toward the advent of relativity assumes that the aether theory, whether of an elastic solid luminiferous medium or of an ultimate and absolute electromagnetic field, was simply replaced by relativity theory, the substitution of the newer and better approach being quite linear and sequential. Physicists generally teach that the rise of relativity occurred after the fall of the aether, but historians must argue that the fall of the aether happened after the rise of relativity.<sup>45</sup>

Albert Michelson and Albert Einstein, the one a paragon of the experimentalist and the other of the theoretician in physics, are generally considered to have produced the cause and the effect, respectively, of the twentieth century’s theories of relativity. How the special theory of relativity grew to be accepted

by a majority in the young profession of physics and how the special theory evolved into the general theory of relativity are provocative questions, but they cannot be answered here. Suffice it to say that after Einstein's General Theory appeared in 1915 and after World War I, the return of the Eddington eclipse expedition with astronomical "proof" of Einstein's theories made front-page news throughout the western world. And incidentally this sort of publicity provoked certain physicists of a more traditional persuasion to reexamine the supposed dialectic between experiment and theory at the base of the new physics.<sup>46</sup>

George Ellery Hale, the astrophysical pioneer and entrepreneur of Mount Wilson, on 19 July 1920, initiated an invitation to Dayton C. Miller, the acoustical expert and successor to Michelson at Case in Cleveland, to come out to Pasadena and to repeat at a 6000-foot altitude and at all four seasons of the year the Michelson aether-drift tests. After six months of study and consultation Miller finally agreed to undertake this project, knowing that Michelson, now in semi-retirement from teaching at Chicago but still intensely active with astrophysical experiments going on in Chicago and southern California, would be at Mount Wilson occasionally and could be counted upon to take an interest in their repetition and refinement. Even Einstein himself had recently tried in his Leyden lecture of 1920 to salvage the aether concept on behalf of Lorentz, and so Miller accepted the task as an eminently respectable one. We know all this and more largely from correspondence in the files of the Director of the Mount Wilson Observatory.<sup>47</sup>

In April 1921, Miller set up the old Morley-Miller steel-based interferometer on top of four concrete piers near the eastern edge of the top of Mount Wilson at an elevation almost ten times that last used in 1906 on Euclid Heights in Cleveland. Another protective observation hut with eisenglass panels was erected around the experimental area and meteorological data were recorded as carefully as the fringe-shift observations during the working period. The immediate results of data reduction, as Miller wired Hale, were four times greater than obtained from the hill above Lake Erie.<sup>48</sup>

Miller's cautious intuition was thus reinforced, and he determined to try again six months later on the opposite side of Earth's orbit and with extra precautions against thermal and magnetic masking effects. While Miller sought counsel from Lorentz (who was then visiting at Cal Tech) and from Einstein (who made a special point of visiting with Miller while on tour in Cleveland), workmen atop Mount Wilson built a more substantial observation hut and cast a concrete cross for a new interferometer base. Meanwhile, Miller and a few associates in Cleveland elaborated their data reduction with harmonic analyses and compared the new results with all those gathered in the observations from 1903 to 1906. These expanded results were startling, but no public mention was made until the November-December 1921 tests confirmed them. Then in the April 1922 issue of *Physical review*, Miller first announced:

The results show a definite displacement, periodic in each half revolution of the interferometer of the kind to be expected, but having an amplitude of one tenth of the presumed amount.<sup>49</sup>

Miller's claim to have achieved an effect "such as would be produced by a true ether-drift" was qualified as a preliminary result requiring further study,

observations, and experimentation. But the thrust of his remarks was clear enough: here was the Secretary of the American Physical Society, a member of the National Academy of Sciences, a renowned expert on acoustics throwing a challenge at Michelson, Einstein, and the whole physics profession. The gravity of such a charge was not lost upon Miller himself: he waxed and waned in his enthusiasm for continuing these tests, being confident neither in his theoretical ability, his data reduction procedures, nor in his experimental design. When on 5 April, 1922, however, Lorentz personally confided to Miller that he had never before actually seen white light fringes in an interferometer, Miller seems to have taken heart. Given this divorce between theoreticians and experimentalists, might it not be indeed the case that relativity theory had gone far beyond its experimental warrant?<sup>50</sup>

Michelson shared this attitude in part, but his various projects with stellar interferometers to measure star diameters, with earth-tide experiments, and with better velocity of light measurements left little time, at his age and state of health, for commiseration. Besides, Michelson's latest project on Mount Wilson was undertaken with Ludwik Silberstein and later Henry G. Gale to test for the effect of the Earth's *rotation*, instead of its *translation*, on the velocity of light. Preliminary runs on the mountain during 1921–23 were unsatisfactory, and so an elaborate rectangular raceway (over 1000' × 2000') was built inside pipes on the surface of a field at Clearing, Illinois. Here it was hoped in 1924 that the hypothesis of a fixed aether would give a result at variance with the predictions of General Relativity theory.<sup>51</sup>

After three years of exhaustive laboratory tests, Miller returned to Mount Wilson in September 1924, expecting to begin a deliberate series of observations "at different times of the year under the same circumstances". In spite of the promise in the classic 1887 Michelson–Morley paper, this had never before been done. Comparing his September 1924 and April 1925 observations with his April and December 1921 readings, Miller found his data reduced once again to a small positive periodic displacement of the interference fringes, and so Miller reported to the National Academy that the effects were shown to be real and systematic, beyond any further question.<sup>52</sup>

Astronomical calculations of solar proper motion, in the tradition of William Herschel, F. W. A. Argelander, and William Huggins, had indicated that tests during December 1924 should give a resultant value for Earth motion near zero, and so Miller dispensed with winter observations and returned to California in April and August 1925 for his penultimate seasonal tests for aether-drift. However, while studying his data, their interpretation, and the extremely difficult problem of the solar apex, Miller became convinced, by Gustaf Strömberg and other Mount Wilson experts on solar motion, that he should abandon all former assumptions regarding a stagnant, dragged, or drifting aether; instead he should concentrate simply on the question, "What is the absolute motion of the Earth through the heavens?", irrespective of any expected result. Heretofore, he claimed, the orbital component had dominated aether-drift experiments; it was time to embark on "an entirely new quest".<sup>53</sup>

Meanwhile, in January and April 1925, the results of the Michelson–Silberstein–Gale experiment to test for Einstein's principle of equivalence became publicized rather embarrassingly and confusedly. This "crucial test" for an

aether-drift connected with the rotation of the Earth, so elaborately planned and executed, turned out to be an apparent \$17,000 fiasco. In recalculating the values of the displacement to be observed, it was discovered that the observed value agreed with both theoretical predictions, and thus both hypotheses (aether-fixed-in-space and Einstein's principle of equivalence) were equally well confirmed. Later, however, the Michelson-Gale experiment was recognized as having proved two propositions: (1) that the Earth's rotation has no effect on the velocity of light, and (2) that the venerable stagnant aether hypothesis of Sir George G. Stokes was definitely untenable.<sup>54</sup>

Miller's new quest for the absolute *translational* motion of the Earth appeared far less equivocal in mid-1925 than the results of the Michelson-Gale experiment on *rotational* motion. So, in spite of his heavy load of administrative duties as president of the American Physical Society that year, Miller persevered to finish his seasonal tests and data reduction in time for his retirement address. This he almost managed to do, and at the Kansas City meeting of the American Association for the Advancement of Science on 29 December 1925, Miller dramatically announced that the absolute motion of the solar system must be about 200 kilometers per second toward the head of the constellation Draco.<sup>55</sup>

So impressed were his colleagues with the immediate sensation of Miller's findings that he was awarded the Third American Association prize of \$1000 for this paper on "The Significance of the Ether-Drift Experiments of 1925 at Mt. Wilson". Although his seasonal observations were still incomplete (for winter) and his distinctions between "absolute motion" of Earth and solar system left much to be desired, the AAAS Award Committee, which included Karl T. Compton of Princeton for physics, tendered its prize to Miller, and this despite the fact that another speaker at that meeting, A. C. Lunn, had pleaded for the emancipation of our world geometry from an undue emphasis on special experiments.<sup>56</sup>

Strangely, hardly anyone except Miller himself drew parallels between Miller's values for the resultant velocity of Earth's various motions with those given by Herschel in the early nineteenth century. The solar apex problem in astronomy, for which Herschel had assigned a direction toward the constellation Hercules (very near Draco on the celestial sphere), was now reinforced by Miller's findings.<sup>57</sup>

Miller's shocking announcement was hard to reconcile with the Michelson tradition and with the Michelson-Gale experiment. Miller's findings seemed to demand almost complete (95%) aether-drag near sea level whereas the Michelson-Gale result seemed to say that an aetherial atmosphere could not be dragged around at all by the Earth's rotation. Michelson himself had already started to plan with Francis Pease at Mount Wilson how to respond experimentally to Miller's challenge, especially after it was made complete by the February 1926 tests. Many other younger physicists around the world also pushed forward to pick up the gauntlet.<sup>58</sup>

Various schemes for checking Miller's "discovery" were hatched but none took seriously Miller's insistence on a translucent optical path. Michelson himself was besieged with inquiries regarding his opinions, and he too instructed his subordinates to begin construction of a far bigger and better interferometer than had ever before been built. Some of Michelson's crew who had worked on

his Earth-tides experiment, his aether-drift test for the rotational motion of the Earth, and his mountain-peak velocity of light measurements volunteered to retry the classical Michelson–Morley experiment once again.<sup>59</sup>

One of the first experimentalists to deny the validity of Miller's results was Roy J. Kennedy who, in the constant temperature basement room of the Norman Bridge Laboratory at California Institute of Technology, constructed an interference device with an optical step-mirror that furnished null results of another order of magnitude. Kennedy was followed by K. K. Illingworth, a graduate student at Cal Tech, who carried Kennedy's refinement of the interferometer a step further and who also tried the experiment on top of Mount Wilson, likewise with null results. But Illingworth's device was set up in the well of the 100-inch Hooker telescope inside the observatory dome; it was Miller's contention that the plane of the optical path had to be translucent for the free passage of the aether.<sup>60</sup>

Meanwhile in France, Auguste Piccard and Ernst Stahel let loose a miniature interferometer enclosed in the gondola of a hot-air balloon in free flight from which was recorded likewise null results. Later, Piccard and Stahel also carried an interferometer to the top of Mt. Rigi, and from there too they again reported null results.<sup>61</sup>

By mid-1926, Michelson and his colleagues had completed construction of a massive Invar interferometer some 30 feet in diameter with a 55-foot light-path, large enough to carry the observer in a bucket-seat during its rotation. However, difficulties with mechanical shear forces and strains during preliminary trials convinced Michelson that this device was simply too complicated and too massive. Consequently Francis Pease and Fred Pearson borrowed the old 7000 lb. cast-iron bedplate that had been built for polishing the 100-inch Hooker mirror and made this plate into the base for a new 85-foot path-length interferometer, above which on stationary flooring the observer and the light source could be fixed while the interferometer turntable rotated beneath them.<sup>62</sup>

In February 1927, a "summit conference" was held at Mount Wilson attended by most of the physicists except Einstein who were interested in the aether-drift tests. Here, Lorentz and Michelson, Miller and Kennedy among others compared their results and their interpretations, and Miller found himself a minority of one. He still could claim, however, to be the only person to have run aether-drift tests at all four seasons of the year, under comparable conditions at the same altitude, and using a translucent optical plane.<sup>63</sup>

The next year, 1928, the Optical Society of America honored Albert Abraham Michelson by dedicating its annual meeting and the proceedings thereof to his works. Michelson reported once again that his latest reruns of the classical experiment gave results as unimpressive as on his first trials almost 50 years earlier. Miller, on the other hand, likewise present, again claimed that his refinements of both the experiment and his own data gave small but definitely positive results. After the completion of his four seasonal tests in 1926 and his reanalyses in 1927, Miller did make a significant amendment to his interpretation, changing an algebraic sign, therefore giving a reciprocal direction to his absolute velocity of the Earth.<sup>64</sup> This change was highly destructive to confidence in Miller's reports.

Meanwhile, in Jena, at the Zeiss Optical Works, the Swiss physicist Georg

Joos developed and carried through experiments with the most elaborate optical aether-drift interferometer ever constructed. This machine, about 12' high with 20' arms, enclosed in helium-bathed optical pathways, used photography to record the results and a fused-quartz base to eliminate magnetostriction. The optical elements to facilitate the multiple reflections and refractions of the light pencils that were recombined to form the fringe-shifts in the light beam, were the best that the Zeiss company could produce. The publication of Joos's null results, together with reaffirmations by Michelson just before he died in 1931, essentially brought to a close physical worries over Miller's work.<sup>65</sup>

In the meantime, of course, quantum theory had progressed so far with the development of matrix mechanics and wave mechanics, and relativity theory was proving itself meaningful in so many ways, that the younger generation could hardly take Miller seriously. Nevertheless, Miller published several more "final" aether-drift papers in 1933–34, as he also returned to his research interests in acoustics.<sup>66</sup> The later experiments of Kennedy and Thorndyke, of Ives and Stilwell, and much later, of Cedarholm, Townes, and Essen prompted by Dirac's effort to revive the electromagnetic aether concept, were yet to come and to furnish more evidence con than pro that Miller was wrong.<sup>67</sup> Miller died in 1941 unrepentant, however, as Michelson had a decade earlier. The next professor of physics at Case in Cleveland, Robert S. Shankland, with Einstein's encouragement led a group in the statistical reanalysis of the whole of Miller's tabular data on high-speed computers in 1954. The outcome of this last and to date most definitive study of Miller's aberrant results seemed to indicate that Hermann von Helmholtz had been right way back in 1880 when he warned Michelson that temperature control might obviate all his results.<sup>68</sup>

#### IV. CONCLUSION

This historical study of the Michelson–Morley–Miller experiments for aether-drift leads us to a set of eight insights evenly divided on the basis of a before-and-after-1905 analysis. The social generalizations that follow are offered as possible contributions to future histories of the aether concept and of relativity theory.

##### A. *Before 1905*

First and most obviously, during the last decade of the nineteenth century and until 1905 the luminiferous aether had merged into an electromagnetic aether, thence into dielectric aethers of many different sorts; but this metamorphosis had in no way diminished the conceptual need most physicists still felt for a medium. In fact, if anything, the aether concept was more firmly established than ever during this period when the marvellous new communication machine called the radio was in its infancy.

Second, Hertz's discovery of wireless waves was more than sufficient to offset, for the time being, any worries certain individuals surely had about the lack of any consistent theory to explain this medium. Hertizian waves were there for all to perceive as experimental evidence confirming Maxwell and reinforcing belief in an all-pervasive medium. Physical opticians and mathematical physicists became ever more concerned over the theoretical contradictions revealed by

radiation studies in the 1890s, but apparently few had yet despaired of finding an eventual solution. Hertz himself was one of the most intense critics of the usual aether theories, but he died without denying the need for a *plenum*.

Third, insofar as the Michelson–Morley experiment itself was known, it posed a problem indeed, but there were many possible explanations for it, and no direct corroborations of it. Besides the fact that Hertz had seemingly bolstered the same aether which Michelson had undermined, Lodge’s test for aether-viscosity seemed in its failure to cancel out the failure to find an aether-wind. Perhaps this double failure simply meant that the Michelson–Morley test was not sensitive enough, after all, to detect so slight an effect. Even though Michelson was trusted beyond question, and his measurements were admirably precise, still at least he, Morley, and Miller knew that the seasonal tests had never been made and that there were some extraordinarily delicate possibilities for unnoticed experimental errors.

Fourth, and finally in the period before 1905, this study has found no other experiments performed *on the exact model* of the Michelson–Morley design or *for that specific purpose* from July 1887 until the summer of 1902. Given the critical nature of the solar and stellar proper motion problem, there is all the more reason to marvel at how this uncompleted, unexplained, optical experiment for Earth’s relative motion blended into the social fabric of theoretical physics to become a part of the scientific revolution and philosophic renaissance of the twentieth century.

### B. After 1905

During the period from 1905 to 1930, four more points emerged as justifiable generalizations from the study of the “afterlife” of Michelson’s aether-drift experiment.

First and foremost, the classic Michelson–Morley experiment derived its importance and significance far more from what it *suggested* than from what it *imposed*. Only by interpretations of it and the several repetitions of it in the 1920s did the experiment eventually become regarded as *crucial*. Oversimplified descriptions, both by relativists and by aether-apologists, gave it a mythic life that made it seem to have been a crucial test for the existence of aether. But that belief is naive history, however well it might have served pedagogic or didactic purposes during the period between 1905 and 1915, that is, between Einstein’s restricted and general theories of relativity. It is a severe anachronism to attribute the death of the aether to Michelson’s experiment of 1887 without qualifying this by drawing attention to both the whole life of the Michelson–Morley–Miller experiment and the concurrent development of relativity and quantum theories and, indeed, of physics as a whole.

Second, the bitter conflict between aether apologists and relativity partisans was in part a problem of “generation gap”, partly a conflict between experimental *versus* theoretical attitudes, and partly a fight between different denominational dogmas regarding mathematical formalism. But among true scientists these differences and the ready-made answers they imply are less important than the questions that prompted them; witness the good will (despite vested interests) of Michelson toward Miller, of Lorentz and Einstein and Miller toward each other, and of Miller toward his critics. If the Michelson–Morley–Miller

experiment had outlived its utility and helped change the quintessential questions of science by 1930, it did so only at the expense of such oversimplifications in the "middle literature" of physics that it became unrecognizable to the three men who performed the tests.

Third, despite Miller's background in acoustics and his mistakes regarding relativity's implications, he alone actually carried out the original intent of the Michelson–Morley experiment to test for aether-drift during four seasons under the same conditions. He alone carried that cosmic intent through laborious calculations with minute experimental readings to offer a set of values for the Earth's cosmic motion.

Fourth, in spite of Miller's controversial and somewhat naive battle for recognition of what he called "the absolute motion of the Earth", the response of Michelson's and that of all the other known experiments were inadequate to meet the conditions Miller specified as necessary, particularly that of the translucent plane of optical path. Two obvious lines of research remain necessary to render a more adequate assessment of the Michelson–Morley–Miller experiment: namely, studies of high-vacuum science and technology, and studies of the difficult astronomical problem of solar and stellar proper motion.

There remains one last question raised by this study that calls for an answer in social and historical terms rather than in terms of mathematical physics or analytical philosophy: Why, in spite of the intense and extensive research by literally thousands of scientists and scholars over the past eight decades, have we so often begged the questions about the origins of relativity theory and about the intricacies and inelegancies of the historical record of the Michelson–Morley–Miller experiments?

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and gross Matter; with some new experiments", *Philosophical transactions*, clxxxiv (1893), 727–804, esp. 753. Cf. Lord Rayleigh, "Aberration", *Nature*, xlv (1892), 499–502.

25. G. F. FitzGerald, "The ether and the Earth's atmosphere", *Science*, xiii (1889), 390. This was a note "lost" even to its author and the first serious reaction to the Michelson-Morley experiment of 1887; it was recently rediscovered by Stephen G. Brush, "Note on the history of the FitzGerald-Lorentz Contraction", *Isis*, lviii (1967), 230–2. Cf. Alfred M. Bork, "The 'FitzGerald' Contraction", *Isis*, lvii (1966), 199–207.
26. Oliver Lodge, *Modern views of electricity*, (2nd ed., London, 1892), first published in 1889, 3rd ed. in 1907; Paul Drude, *Physik des Aethers auf Elektromagnetischer Grundlage* (Stuttgart, 1894); A. E. Dolbear, *Matter, ether, and motion: The factors and relations of physical science* (2nd ed., Boston, 1894). Cf. David L. Anderson, *The discovery of the electron: The development of the atomic concept of electricity* (Princeton, 1964).
27. Wilhelm Konrad Röntgen, "On a new form of radiation", *Nature*, liii (1896), 274; Albert A. Michelson, "A theory of the 'X-rays'", *American journal of science*, (4) i (1896), 312–4. See also Bern Dibner, *The new rays of Professor Roentgen* (Norwalk, 1963).
28. A. A. Michelson, "The relative motion of the Earth and the ether", *American journal of science*, (4) iii (1897), 475–8.
29. E. W. Morley and H. T. Eddy, "On the velocity of light in a magnetic field", *Proceedings of the A.A.A.S.*, xlix (1890), 81; Morley and D. C. Miller, *ibid.*, xlvii (1898), 123, and *Physical review*, vii (1898), 283–95.
30. H. A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (Leiden, 1895, reprinted Leipzig, 1906); Joseph Larmor, *Aether and matter: A development of the dynamical relations of the aether to material systems on the basis of the atomic constitution of matter, including a discussion of the influence of the Earth's motion on optical phenomena . . .* (Cambridge, 1900). See also L. L. Whyte, "A forerunner of twentieth century physics: A re-view of Larmor's 'Aether and matter'", *Nature*, clxxxvi (1960), 1010.
31. Lord Kelvin [Sir William Thomson], *Baltimore lectures on molecular dynamics and the wave theory of light* (London, 1904), 485–527. See also Thomson's *Popular lectures and addresses* (3 vols., London, 1891–94), especially ii, 535–56.
32. Henri Poincaré, *Science and hypothesis*, trans. W. J. G. [sic.] (New York, 1952), 171, first published in French in 1902; *Science and method*, trans. F. Maitland (New York, n.d.), 216–21, first published in French in 1904 [?]; *The value of science*, trans. G. B. Halstead (New York, 1958), 99, first published in French in 1905; and *Mathematics and science: Last essays*, trans. J. W. Bolduc (New York, 1963), 89–99, from first edition *Dernières pensées* (Paris, 1913). See also Poincaré's praise of Michelson's experiment at the St. Louis Exposition in 1904: "The principles of mathematical physics", trans. G. B. Halstead, *The monist*, xv (1905), 10. See also Gerald Holton, "On the thematic analysis of science: The case of Poincaré and Relativity", in *Mélanges Alexandre Koyré* (2 vols., Paris, 1964), ii, 257–69. H. A. Lorentz, *Lectures on theoretical physics*, trans. L. Silberstein and A. P. H. Trivelli (3 vols., London, 1927–31), especially "Aether theories and aether models" delivered at University of Leyden, 1901–2, vol. i, 3–71; *The theory of electrons and its applications to the phenomena of light and radiant heat* (New York, 1909), lectures delivered at Columbia, March–April, 1906, 195–6, 230; 2nd ed., New York, 1915. See also Paul Drude, *The theory of optics*, trans. C. R. Mann and R. A. Millikan (New York, 1901), 478–82 on Michelson-Morley and interpretation.
33. See, e.g., Sir Oliver Lodge, *The ether of space* (London, 1909); also translated into German by H. Barkhausen, *Der Weltäther* (Braunschweig, 1911); Joseph Larmor, "Aether", article in *Encyclopaedia Britannica*, eleventh edition (London and New York, 1910–11), i, 292–97; Arthur Schuster, *The progress of physics during 33 years, 1875–1908* (Cambridge, 1911), 109; M. G. Sagnac, "L'éther lumineux démontré par l'effet du vent relatif d'éther dans interférométrie en rotation uniforme", *Comptes rendus*, clvii (1913), 708–10, and 1410–3; William Magie, "The primary concepts of physics", *Science*, xxxv (1912), 281–93; Leigh Page, "Relativity and the ether", *American journal of science*, (4) xxxviii (1914), 169–87; Gustave LeBon, *The evolution of forces* (New York, 1908), 13–17; Augusto Righi, "L'expérience de Michelson et son interpretation", *Comptes rendus*, clxviii (1919), 837–42; "Sur les bases expérimentales de la Théorie de la Relativité", *Comptes rendus*, clxx (1920), 497–501 and 1550–4; Richard C. Maclaurin, *The theory of light: A treatise on physical optics* (Cambridge, 1908), 10, 16, 32; Frederick Soddy, *Matter and energy* (London, 1912), 184–5; D. N. Mallik, *Optical theories* (Cambridge, 1917), 171. J. J. Thomson even defended the aether on occasion: see, e.g., "On the light thrown by recent investigations on electricity on the relation between matter and ether", the Adamson lecture, 4 November 1907 (Manchester University [Press] Lecture No. 8, 1908), 7, 21; *Beyond the electron* (Cambridge, 1928), 13–15; *Recollections and reflections* (New York, 1937), 432; and George P. Thomson, *J. J. Thomson and the Cavendish Laboratory in his day* (London, 1964), 13, 37, 155–7.

34. Lord Rayleigh, “Does motion through the aether cause double refraction?”, *Philosophical magazine*, (6) iv (1902), 678–83; F. T. Trouton and H. R. Noble, “The mechanical forces acting on a charged electric condenser moving through space”, *Philosophical transactions*, ccii (1903), 165–81; D. B. Brace, “On double refraction in matter moving through the aether”, *Philosophical magazine*, (6) vii (1904), 317–29. Regarding the supposed constancy of the velocity of light, see M. E. J. Gheury, “The velocity of light: History of its determination from 1849 to 1933”, *Isis*, xxv (1936), 437–48; N. Ernest Dorsey, “The velocity of light”, *Transactions of the American Philosophical Society*, (2) xxxiv (1944), Part I, 2–87; J. H. Sanders *Velocity of light* (Oxford, 1965), and R. S. Shankland, “Final velocity-of-light measurements of Michelson”, *American journal of physics*, xxxv (1967), 1095.
35. Michelson’s 1899 Lowell lectures, for instance, ended with far more confidence in “The ether” than in the aether-drift experiment: *Light waves and their uses* (Chicago, 1903), 156–63. See also C. Riborg Mann, *Manual of advanced optics* (Chicago, 1902), 48, 170, with introduction by A. A. Michelson. Another significant effort to treat the electromagnetic aether *sui generis* came from Dmitri I. Mendeléev who tried to fit the ether underneath his periodic table as an inert gas: D. Mendeléef, [sic.] *An attempt towards a chemical conception of the ether*, trans. G. Kamensky (London, 1904).
36. William M. Hicks, “On the Michelson–Morley experiment relating to the drift of ether”, *Philosophical magazine*, (6) iii (1902), 9–36, cf. 256, 555, and *Nature*, lxxv (1902), 343; W. Wien, “Über die Differentialgleichungen der Elektrodynamik für bewegte Körper”, *Annalen der Physik*, (4) xiii (1904), 641–77; A. A. Michelson, “Relative motion of the Earth and aether”, *Philosophical magazine*, (6) viii (1904), 716–9; “The velocity of light”, in *The Decennial publications of The University of Chicago*, ix (Chicago, 1904), 3–10; E. W. Morley and D. C. Miller, “On the theory of experiments to detect aberrations of the second degree”, *Philosophical magazine*, (6) ix (1905), 669–80.
37. E. W. Morley and D. C. Miller, “Extract from a letter to Lord Kelvin”, *Philosophical magazine*, (6) viii (1904), 753–4; “Report of an experiment to detect the FitzGerald–Lorentz Effect”, *Proceedings, American Academy of Arts and Sciences*, xli (Boston, 1906), 321–8; also abridged in *Philosophical magazine*, (6) ix (1905), 680–5.
38. H. A. Lorentz, “Electromagnetic phenomena in a system moving with any velocity less than that of light” from *Proceedings, Academy of Science* (Amsterdam), vi (1904), 809, as reprinted in the A. Sommerfeld collection, *The Principle of Relativity*, trans. W. Perrett and J. B. Jeffrey (London and New York, 1923), 22, 29. See also Kenneth F. Schaffner, “The Lorentz–FitzGerald Contraction and the Lorentz Electron Theory” [preprint paper], 6–12; Paul Ehrenfest, “H. A. Lorentz as researcher” in *Collected scientific papers*, ed., Martin J. Klein (Amsterdam, 1959), 471–8.
39. H. Minkowski, “Space and time”, address to the 80th Assembly of German Natural Scientists and Physicians at Cologne, 21 September 1908, in the Dover reprint of *The Principle of Relativity*, 75–96.
40. Dayton C. Miller, *op. cit.*, *Reviews of modern physics*, v (1933), 217. It is perhaps significant that Miller failed to mention or cite the following notices: E. W. Morley and D. C. Miller, “Report of progress in experiments on ether drift”, *Science*, (2) xxiii (1906), 417, and “Final report on ether-drift experiments”, *Science*, (2) xxv (1907), 525.
41. H. R. Williams, *Edward Williams Morley*, 215; D. T. MacAllister, ed., *The Albert A. Michelson Nobel Prize and Lecture*, Publication of the Michelson Museum, No. 2 (China Lake, Calif. 1966), aptly indicates that the Prize was awarded for everything but the aether-drift experiments; Robert S. Shankland, “Dayton C. Miller: Physics across fifty years”, *American journal of physics*, ix (1941), 273–83.
42. Einstein, “Zur Elektrodynamik bewegter Körper”, *Annalen der Physik*, (4) xiv (1905), 891, and in the Dover reprint of *The Principle of Relativity*, 38.
43. A. Einstein, “Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt”, *Annalen der Physik*, (4) xvii (1905), 132–48; “Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen”, *ibid.*, 549–60; and “Zur Elektrodynamik bewegter Körper”, in the Perret and Jeffrey translation in Dover reprint of *The Principle of Relativity*, 48.
44. In addition to the Holton papers cited above (especially in n. 4), see also his “Mach, Einstein, and the search for reality”, *Daedalus* (Proceedings of the American Academy of Arts and Sciences), xcvi, pt. 2 (Spring, 1968), 636–73; L. Pearce Williams, ed., *Relativity Theory: Its origins and impact on modern thought* (New York, 1968); Paul A. Schilpp, ed., *Albert Einstein: Philosopher–scientist* (2 vols., New York, 1959), first published 1949–51 in The Library of Living Philosophers series; Sir Edmund Whittaker, *A history of the theories of aether and electricity* (2 vols., rev. and enlarged ed.; London, 1951–53), and in Harper Torchbook

edition, 1960; also Whittaker's *From Euclid to Eddington: A study of conceptions of the external world* (London, 1949), 47–96. In addition publications related to the advent of relativity theory may result from graduate studies by Daniel J. Kevles, Lawrence Badash, Dennis F. Miller, Stanley Goldberg, Antony Ruhan, and Bert K. Collins. Among the general works extant and essential to such a study are the following: P. W. Bridgman, *A sophisticate's primer of Relativity* (Middletown, Conn., 1962); Mary B. Hesse, *Forces and fields: The concept of action at a distance in the history of physics* (New York, 1962); Max Jammer, *Concepts of space: The history of theories of space in physics* (Cambridge, Mass., 1954), and *The conceptual development of quantum mechanics* (New York, 1966); Thomas S. Kuhn, John L. Heilbron, Paul Forman, Lini Allen, *Sources for history of quantum physics: An inventory and report* (Philadelphia, 1967); Michael Polanyi, *Personal knowledge: Towards a post-critical philosophy* (Chicago, 1958); Karl R. Popper, *The logic of scientific discovery* (New York, 1959), revised and translated from German edition of 1934; G. H. Keswani, "Origin and concept of Relativity", Parts I and II, *British journal for the philosophy of science*, xv (1965), 286–306 and xvi (1966), 19–32.

45. See n. 3 above. The foreshortening and abridgment of the period of conflict over relativity is natural to the "Whig" perspective, but the lens of critical historians will not miss such evidence as Michele LaRosa, *Der Äther, Geschichte einer Hypothese*, trans. K. Muth (Leipzig, 1912); Maurice Gandillot, *L'Éthérique: Essai de physique expérimentale* (Paris, 1923); Aloys Müller, *Das Problem des Absoluten Raumes und Seine Beziehung Zum Allgemeinen Raumproblem* (Braunschweig, 1911); Hans Witte, "Weitere Untersuchungen über die Frage nach einer mechanischen Erklärung der elektrischen Erscheinungen unter der Annahme eines kontinuierlichen Weltäthers", *Annalen der Physik*, (4) xxvi (1908), 235–311. For a different kind of ferment relevant to the genesis of the special theory of relativity, see the debate between Adolf Grünbaum and Michael Polanyi in H. Feigl and G. Maxwell, eds., *Current issues in the philosophy of science: Symposia of scientists and philosophers* (New York, 1961), 43–55. And for another long-standing debate between Herbert Dingle and W. H. McCrea, see "Don't bring back the ether", *Nature*, ccxvi (1967), 113–24.
46. Other experiments bearing on the aether-drift/relativity problem in the meantime included those of W. Kaufman, "Über die Konstitution des Elektrons", *Annalen der Physik*, (4) xix (1906), 487–553; A. H. Bucherer, "Die experimentelle Bestätigung des Relativitätsprinzips", *Annalen der Physik*, (6) xxviii (1909), 513–36; F. T. Trouton and A. O. Rankine, "On the electrical resistance of moving matter", *Proceedings of the Royal Society*, lxxx (1908), 420–435; Pieter Zeeman, "Optical investigation of ether-drift", *Nature*, xcvi (1915), 430–1; Q. Majorana, "O. the second postulate of the Theory of Relativity", *Philosophical magazine*, (6) xxxv (1918), 163–74; "Experimental demonstration of the constancy of the velocity of light emitted by a moving source", *Philosophical magazine*, (6) xxxvii (1919), 145–9.
47. Letter, George E. Hale to Dayton C. Miller, 19 July 1920, in Miller Correspondence File, Director, Mount Wilson Observatory, Pasadena, California. I am indebted to Ira S. Bowen for access and permission to study these materials. Unless otherwise indicated all letters and telegrams hereafter cited are located in the Mount Wilson Director's Correspondence files: Letter, Miller to Hale, 1 November 1920; letter, E. Merritt (Physics, Cornell) to Hale, 22 November 1920; letter Walter S. Adams to Merritt, 29 November 1920; telegram, D. C. Miller to Hale, 19 January 1921; letter, D. C. Miller to Hale, 10 February 1921. Albert Einstein, *Äther und Relativitätstheorie* (Berlin, 1920) (p. 15: "space without ether is unthinkable"); cf. H. A. Lorentz, *The Einstein Theory of Relativity: A concise statement* (New York, 1920), 60–3.
48. Telegram, D. C. Miller to Hale, 22 April 1921; letter, D. C. Miller to Hale, 30 June 1921; cf. Dayton C. Miller, *The science of musical sounds* (New York, 1916).
49. Dayton C. Miller, "Ether-drift experiments at Mount Wilson Solar Observatory", *Physical Review*, xix (1922), 407–8; cf. *Science*, lv (1922), 496. Soon thereafter E. H. Kennard was to call in question another famous pre-1905 test: "The Trouton-Noble Experiment", *Electrodynamics of moving media*, Part iv, *Bulletin of National Research Council*, iv, pt. 24 (1922), 162–72.
50. Letter, Hale to D. C. Miller, 28 July 1921; letter, D. C. Miller to H. A. Lorentz, 22 August 1921; letter, D. C. Miller to Hale, 26 August 1921. R. S. Shankland, S. W. McCuskey, F. C. Leone, and G. Kuerti, "A new analysis of the interferometer observations of Dayton C. Miller", preprint paper [later revised for publication to exclude most of the purely historical references; published in *Reviews of modern physics*, xxvii (1955), 167], 5; cf. H. A. Lorentz, *Problems of modern physics* (Boston, 1927), 1, 221 for aether at Cal Tech lectures in 1922.
51. Letter, A. A. Michelson to Hale, 31 October 1922; letter, A. A. Michelson to L. Silberstein, 28 July 1921 in F. Twyman, *Physical Society* (London) *proceedings*, xliii (1931), 625–32; letter Henry G. Gale to J. H. Tufts, 13 February 1924 in A. A. Michelson papers, The University of

Chicago Library. For Silberstein's prior interests, see L. Silberstein, *The Theory of Relativity* (London, 1914), 72–88; *The Theory of General Relativity and Gravitation* (Toronto, 1922).

52. Letter, D. C. Miller to Hale, 15 June 1922; letter, D. C. Miller to Gano Dunn, 6 December 1922; telegram, D. C. Miller to Walter S. Adams, 3 January 1923; Dayton C. Miller, "Ether-drift experiments at Mount Wilson", *Proceedings of the National Academy of Sciences*, xi (1925), 306–14. Hale retired as Director of Mount Wilson in March 1922; Adams was less sympathetic. Charles L. Poor, a professor of Celestial Mechanics at Columbia, in his *Gravitation versus Relativity* (New York, 1922) used Miller's results to attack Einstein, thus severely damaging Miller's cause.
53. Letter, D. C. Miller to Walter S. Adams, 21 May 1924; telegram, D. C. Miller to Adams, 28 July 1924; letter, D. C. Miller to Adams, 8 December 1924; telegram, D. C. Miller to Adams, 9 March 1925; letter, D. C. Miller to Adams, 21 May 1925; letter, Adams to Miller, 5 June 1925; letter, Miller to Adams, 9 July 1925; letter, Miller to Adams, 19 December 1925. Regarding astronomical relative motions, see William W. Campbell, *Stellar motions with special reference to motions determined by means of the spectrograph* (New Haven, 1913); A. S. Eddington, *Stellar movements and the structure of the universe* (London, 1914); cf. R. J. Trumpler and H. F. Weaver, *Statistical astronomy* (Berkeley, 1953). The work of Lewis Boss, G. W. L. Struve, Simon Newcomb, and W. W. Campbell all gave different answers to the problem of the speed and direction of solar motion, but Campbell's studies around 1913 seemed impressive and offered the tentative values of about 20 km/sec. toward a point on the celestial sphere between Hercules and Lyra (Right Ascension  $271^\circ$ ; Declination  $+31^\circ$ ); see Campbell, *op. cit.*, 143; cf. 126, 134.
54. A. A. Michelson, with Henry G. Gale and Fred Pearson, "The effect of the Earth's rotation on the velocity of light", *Astrophysical journal*, lxi (1925), 137–45; A. A. Michelson, "Light waves as measuring rods for sounding the infinite and the infinitesimal", *The University* [of Chicago] *record*, xi (April, 1925), 153; *New York times*, 9 January 1925, 2.
55. Dayton C. Miller, *op. cit.*, (n. 52); "Significance of the ether-drift experiments of 1925 at Mt. Wilson", *Science*, lxxiii (1926), 433–43; cf. W. F. G. Swann, "The relation of the restricted to the General Theory of Relativity and the significance of the Michelson-Morley Experiment", *Science*, lxxii (1925), 145–8.
56. The prize committee included W. C. Mendenhall for geology, H. P. Cady for chemistry, H. C. Cowles for botany, and C. E. Seashore for psychology: *Science*, lxxiii (1926), 105; cf. A. C. Lunn, "Experimental science and world geometry", *ibid.*, 579–86.
57. J. J. Nassau and P. M. Morse, "A study of solar motion by harmonic analysis", *Astrophysical journal*, lxxv (1927), 73–85. On Herschel's studies, see Michael A. Hoskin, *William Herschel and the construction of the heavens* (London, 1963), 27–59. Of the many other students of stellar motions, including Vesto M. Slipher, Willem de Sitter, Jacobus C. Kapteyn, and J. H. Oort, only two seem to have had direct contact with Miller's work: see Gustaf Strömberg, "Space structure and motion", *Science*, lxxvi (1932), 447–81, 504–8; Edwin Hubble, *The realm of the nebulae* (New Haven, 1936 [reprinted, 1958], 107–14, and *The observational approach to cosmology* (Oxford, 1937).
58. Telegram, D. C. Miller to Walter S. Adams, 27 December 1925; letter, Adams to Miller, 7 January 1926; telegram, Miller to Adams, 18 April 1926; letter, A. A. Michelson to G. E. Hale, 10 September 1925.
59. A. A. Michelson, "Light waves as measuring rods for sounding the infinite and the infinitesimal", 136–53. Cf. Rudolf Tomaschek, "Über das Verhalten des Lichtes ausserirdischer Lichtquellen", *Annalen der Physik*, lxxiii (1924), 105–26. See also the discussion in Michelson's second and last book which must then have been in preparation: *Studies in optics* (Chicago, 1927), 149–61.
60. Roy J. Kennedy, "A refinement of the Michelson–Morley Experiment", *Proceedings of the National Academy of Sciences*, xii (1926), 621–9; cf. *Physical review*, xx (1922), 26–33; K. K. Illingworth, "A repetition of the Michelson–Morley Experiment using Kennedy's refinement", *Physical review*, xxx (1927), 692–6.
61. A. Piccard and E. Stahel, "L'expérience de Michelson réalisée en ballon libre", *Comptes rendus*, clxxxiii (1926), 420–1; "Sur le vent d'éther", *Comptes rendus*, clxxxiv (1927), 451–2; "L'absence du vent d'éther au Rigi", *Comptes rendus*, clxxxv (1927), 1198–1200.
62. Letter, A. A. Michelson to George E. Hale, 10 September 1925; letter, Walter S. Adams to Michelson, 24 November 1927; letter, Adams to Michelson, 1 December 1926; letter, Michelson to Adams, 11 June 1927. A. A. Michelson, F. G. Pease, F. Pearson, "Repetition of the Michelson–Morley Experiment", *Journal of the Optical Society of America*, xviii (1929), 181–2.

63. A. A. Michelson, H. A. Lorentz, *et. al.*, "Conference on the Michelson-Morley Experiment . . .", *Astrophysical journal*, lxxviii (1928), 341-402. Dayton C. Miller, "Ether-drift experiments at Mount Wilson in February 1926", *Physical review*, xxvii (1926), 812; "Report on the ether-drift experiments at Cleveland in 1927", *Physical review*, xxix (1927), 924.
64. See *Journal of the Optical Society of America*, xviii, pt. 3 (March, 1929), 181-2; also Carnegie Institution of Washington, *Yearbooks*, xxvii (1928), 150-1, and xxviii (1929), 143; cf. Waldemar Kaempfert, "Michelson: The apostle of light", *New York times magazine*, 20 November 1927, 1. For a parallel interview of Michelson and Miller, see *New York times*, 3 November 1928, 21.
65. Georg Joos, "Die Jenaer Wiederholung des Michelsonversuchs", *Annalen der Physik*, (5), vii (1930), 385-407, and Joos's *Theoretical physics*, trans. I. M. Freeman (New York, 1934, first published in German in 1932), 227. Cf. D. C. Miller, "Comments on Dr Georg Joos's criticism of the ether-drift experiment", *Physical review*, xlv (1934), 114. See also A. A. Michelson, F. Pease and F. Pearson, "Repetition of the Michelson-Morley Experiment", *Nature*, cxxiii (1929), 88; and Francis G. Pease, "Ether-drift data", *Publications of the Astronomical Society of the Pacific*, xlii (1930), 197-202.
66. Letter, D. C. Miller to G. S. Fulcher, 12 February 1938, in Fulcher Collection at American Institute of Physics Bohr Library. Dayton C. Miller, "The ether-drift experiment and the determination of the absolute motion of the Earth", *Reviews of modern Physics*, v (1933), 203-34; "The absolute motion of the solar system and the orbital motion of the Earth determined by the ether-drift experiment", *Physical review*, xliii (1933), 1054; "The ether-drift experiment and the determination of the absolute motion of the Earth", *Nature*, cxxxiii (1934), 162-4. See also Miller's books of the 1930s: *Anecdotal history of the science of sound* (New York, 1935), and his *Sparks, lightning, and cosmic rays An anecdotal history of electricity* (New York, 1939).
67. Roy J. Kennedy and Edward M. Thorndyke, "Experimental establishment of the relativity of time", *Physical review*, xlii (1932), 400-18; Herbert E. Ives and G. R. Stillwell, "An experimental study of the rate of a moving atomic clock", *Journal of the Optical Society of America*, xxviii (1938), 215-20; P. A. M. Dirac, "Is there an aether?", *Nature* clxiii (1951), 906; L. Essen, "A new aether-drift experiment", *Nature*, clxxv (1955), 793-4; J. P. Cedarholm, G. F. Bland, B. L. Havens, and C. H. Townes, "New experimental test of Special Relativity", *Physical review letters*, i (1958), 342-3; T. S. Jaseja, A. Javan, C. H. Townes, "Frequency stability of He-Ne masers and measurements of length", *Physical review letters*, x (1963), 165-7; K. C. Turner and H. A. Hill, "New experimental limit on velocity dependent interactions of clocks and distant matter", *Physical review*, cxxxiv (1964), 252-6; S. A. Bludman and M. A. Ruderman, "Possibility of the speed of sound exceeding the speed of light in ultradense matter", *Physical review*, clxx (1968), 1176-84.
68. R. S. Shankland, S. W. McCuskey, F. C. Leone, and G. Kuerti, "A new analysis of the interferometer observations of Dayton C. Miller", *Reviews of modern physics*, xxvii (1955), 167-78; Robert S. Shankland, "Conversations with Albert Einstein", *American journal of physics*, xxxi (1963), 47-57.