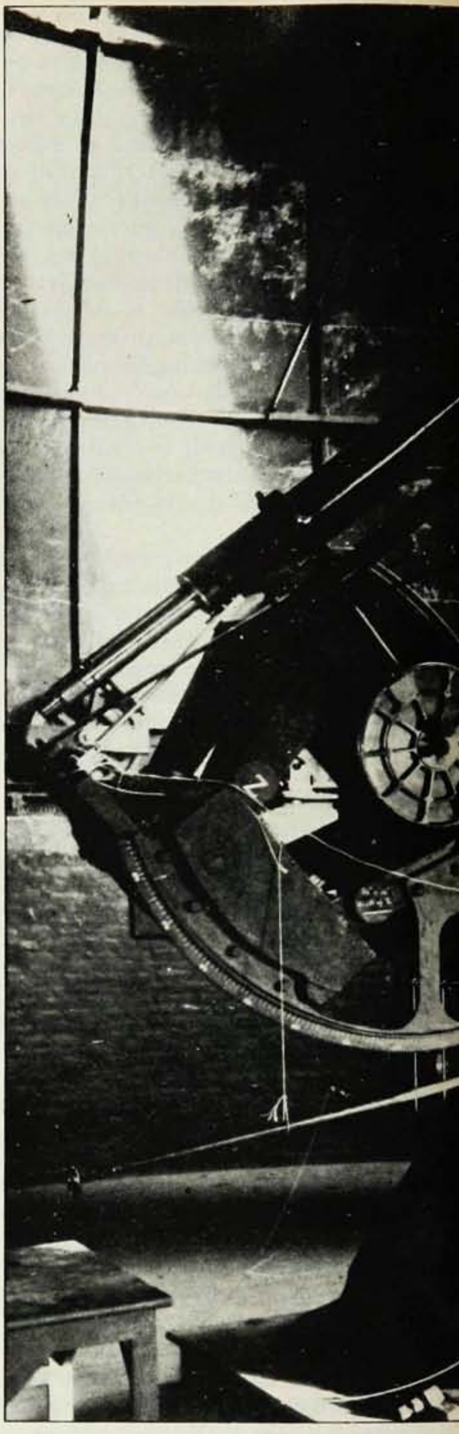
James E. Keeler pioneer astrophysicist

At the Allegheny and Lick observatories, both of which he served as director, Keeler applied physical methods to the analysis of planets, stars and nebulae.

Donald E. Osterbrock



In late December 1877 James E. Keeler appeared at Johns Hopkins University to begin his studies in physics and astronomy.[1] He was a "raw country boy" from Florida, without benefit of a high-school education. Twenty years later, an outstanding astronomer, he was appointed Director of Lick Observatory, the best-known research institution of that era. Two years later he died unexpectedly of a stroke. Keeler had a brilliant career in astronomy and was, with his younger friend George Ellery Hale, one of the great American pioneers of the new science of astrophysics. His observational discoveries are described in every astronomical textbook today, although often his name is not mentioned, and the research techniques that he developed and the problems that he studied still form the basis of much of modern-day astrophysics. The portrait on the opposite page shows him at the height of his career.

A "roving disposition"

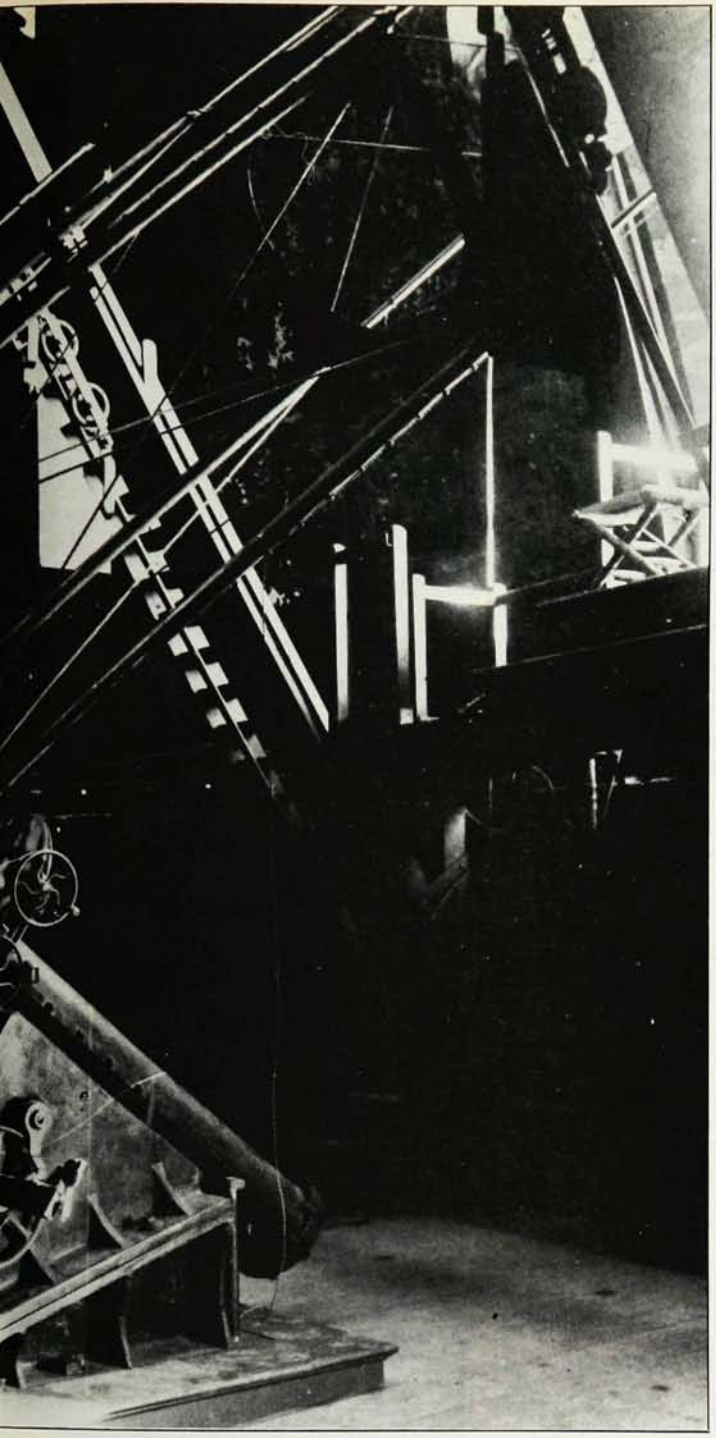
Keeler was born in La Salle, Illinois on 10 September 1857. His father, William F. Keeler, was a native of upstate New York, a restless, pioneering type from whom Keeler inherited his mechanical aptitude and practical skills, as well as the "roving disposition" that took him back and forth across the country three times in his scientific career. William Keeler sailed around the Horn to California during the Gold Rush, then continued on to China and around the world before returning to New York. James Keeler's mother Anna was the daughter of Henry Dutton, Governor of Connecticut from 1854 to 1858 and longtime Head of the Yale Law School. From her Keeler inherited his connections with the New England educational establishment, and his wife always considered him a Connecticut Yankee, in spite of his Illinois birth and Florida upbringing.

After serving in the Union Navy during the Civil War, William Keeler moved with his family to Mayport, Florida, near Jacksonville. He operated a small general-repair business, grew pecans and oranges, and served as a part-time customs officer and post-office auditor. His son James had attended public schools in La Salle until he was twelve, but there was no school in Mayport remotely matching his abilities or interests, and all his further education, until he left for college at the age of 20, was at home. He became interested in astronomy and built his first telescope, a 2-inch refractor, with lenses ordered from a dealer in Philadelphia.

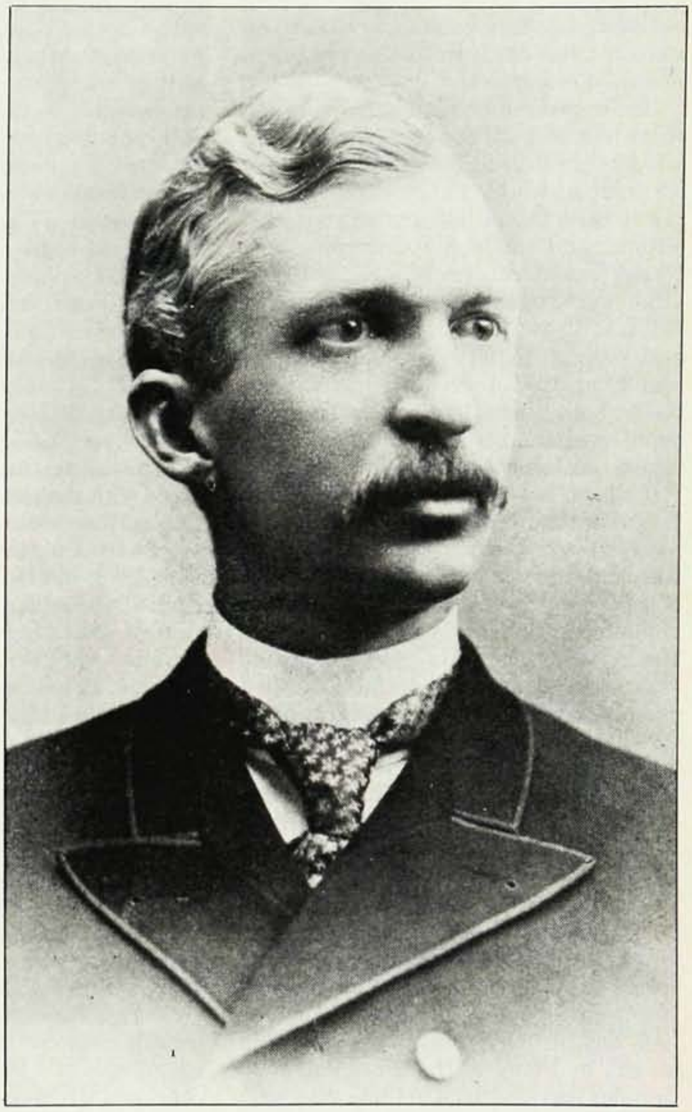
In 1877 Keeler went North in search of a scientific education. A wealthy amateur astronomer, Charles Rockwell, who was distantly connected with Keeler's family, heard about his astronomical interests and offered to finance his education. Keeler entered Johns Hopkins just a few days before Christmas 1877, with no apparent ill effects from being several months late for the start of the term, nor from his irregular educational background. Johns Hopkins was then very new (the first students had entered only one year before Keeler) and strongly emphasized research and graduate education. Henry Rowland was the Professor of Physics, but he had little to do with undergraduate teaching; Keeler learned most of his physics from Charles S. Hastings, a young Yale PhD who was then the only other physics faculty member at Johns Hopkins. In addition to studying physics, German, mathematics, astronomy and chemistry, Keeler had a part-time job as a laboratory assistant and did some numerical computing for an astronomical almanac to help pay his expenses.

At the end of his freshman year Keeler had an unusual research opportunity. He went to Central City, Colorado, with a group under the leadership of Edward S. Holden of the Naval Observatory, to observe the total solar eclipse of 29 July 1878. The party included Hastings, who tried to measure the polarization of the solar corona at the eclipse, and Rockwell, who paid his own and Keeler's expenses. Keeler observed the eclipse with a small, short-focal-length telescope and produced a very creditable drawing of the corona, (page 42) showing the equatorial extensions characteristic of sunspot minimum. It was published in his first scientific

Donald E. Osterbrock is Director of Lick Observatory. He has done research on stellar interiors, the outer layers of the sun, gaseous nebulae and active nuclei of galaxies.



James Keeler and one of his telescopes. The portrait shows him in 1896, when he was director of the Allegheny Observatory and an editor of the Astrophysical Journal. Two years later he was appointed director of Lick Observatory, a post which he held until his death in 1900. The Crossley reflecting telescope, with a 36-inch primary mirror, was used by Keeler at Lick in 1898–1900. The wedge-shaped section at the bottom of the mounting converts the polar axis from the latitude of England to that of Mount Hamilton. The iron casting did not have quite the right angle, so the top of the pier was given a slight tilt. Both photos are from the Lick Observatory Archives.



paper, a two-page contribution in the Naval Observatory report on the eclipse.[2] Hastings, Rockwell and Keeler observed the eclipse from the roof of the Teller House in Central City. (This was still pioneer country; Central City is 450 miles south of the spot on the Little Big Horn where Custer and five troops of the Seventh Calvary had been wiped out by Crazy Horse, Gall and their Sioux and Cheyenne warriors just two summers before.)

In 1881, when Keeler graduated from Johns Hopkins, he was hired by Samuel P. Langley, Director of the Allegheny Observatory in Pittsburgh, as his assistant, and his first job was to go on a scientific expedition to Mount Whitney, California. Langley (page 42), then just under 50 years old was a largely self-taught pioneer "new astronomer" or astrophysicist of the generation before Keeler's. He concentrated his research efforts on the Sun, a sensible decision considering the smoky Pittsburgh sky. He began with visual studies of sunspots, but soon was developing methods and instruments to push quantitative measurements of the solar radiation as far as possible into the then almost unknown infrared spectral region.[3] His expedition to Mount Whitney, a peak 14 500 feet high, was planned to get above much of the Earth's atmosphere, in order to measure the total amount of radiation from the Sun ("the solar constant") in clear, thin, relatively absorption-free air. Furthermore, by comparing measurements made at the peak with measurements made nearly simultaneously close to sea level, it would be possible to determine directly the absorption and thus eliminate it. Mount Whitney was the closest possible equivalent of the present-day artificial satellite from which Langley could observe.

On this expedition Keeler had many chances to demonstrate his ingenuity and practical talents in solving the problems of making accurate measurements with delicate scientific instruments under conditions of extreme sunshine, wind, dust, heat and cold. Langley and Keeler returned with a lot of good data, including spectral observations of the Sun at longer wavelengths than any previously made. Back in Pittsburgh, Keeler worked on reducing and analyzing the measurements, including considerable laboratory work to determine a wavelength scale in the "dark-heat" (infrared) spectral region. The main result was a detailed map of the solar spectrum out to beyond 2 microns, showing many absorption or "cold" bands which, as Langley deduced by comparing the Mount Whitney and low-altitude observations, all originate in the Earth's atmosphere. Keeler, whom Langley considered more of a collaborator than an assistant, was being trained on the job in scientific research.[4]

Keeler realized he needed more formal education, and applied for and received a scholarship to return to Johns Hopkins for graduate work. Langley however was not anxious to lose his capable young assistant, and made a counteroffer. If Keeler would remain at Allegheny another year, Langley would arrange for William Thaw, a Pittsburgh millionaire and philanthropist who supported research at the observatory, to finance Keeler's studies in Germany the following year. Keeler accepted this plan and declined the Johns Hopkins scholarship.[5]

Thus, in May 1883 Keeler sailed from Baltimore to Bremen and spent the next 14 months in Germany. The main lecture courses he attended were on the wave theory of light by Georg Quincke at Heidelberg, and on general physics by Hermann Helmholtz and Heinrich Kayser in Berlin, but he also studied chemistry under Robert Bunsen and differential equations under Carl Runge. Keeler brought with him to Berlin a large diffraction grating that Rowland had given him, and a bolometer that Langley had lent him, and used these instruments in his laboratory work in Helmholtz's Physical Institute. He measured the infrared absorption of CO_2, a problem suggested by his work with Langley, and the results formed the basis of his first astrophysical paper.[6] In a year's time he had had a crash postgraduate course taught by many of the great names in German science, which in those days were the great names in world science.

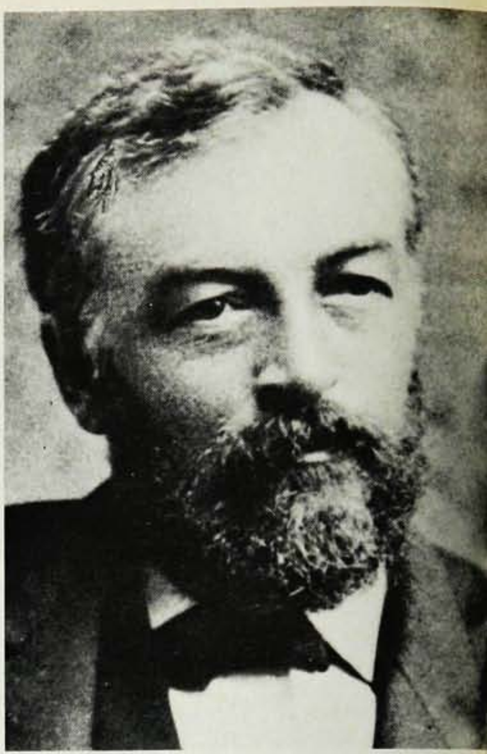
After Keeler returned to the United States, he worked with Langley another two years on infrared measurements of the Sun and Moon, and the related laboratory spectroscopy. But he chafed for wider horizons and more action. He began thinking of moving on to the Coast Survey or the Army Signal Service, but he was saved for astrophysics by a job offer from California.

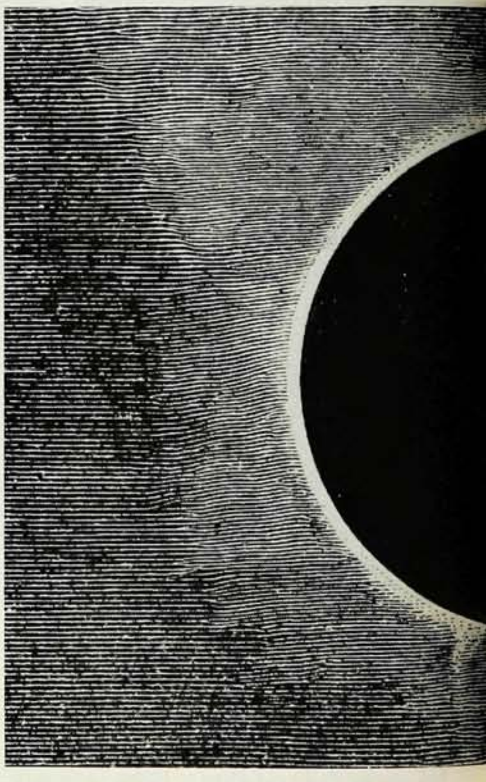
Lick Observatory

The first mountain-top observatory in America, Lick Observatory, was then nearing completion on Mount Hamilton, California. Its telescope, a 36-inch refractor, would be the largest in the world. The Director was to be Holden, who had led the eclipse expedition to Colorado back in 1878. He was now serving temporarily in Berkeley as President of the University of California, and he wanted to have a trained professional astronomer on the scene at the observatory as it was being completed. Keeler was hired and began work in April 1886. His first job was to get the transit instrument adjusted and set up a telegraphic time service (opposite page), which was to be a source of income to Lick Observatory as it had been at Allegheny. He worked closely with Captain Richard S. Floyd, the San Francisco man of affairs who, as President of the Lick Trust, planned and directed the building of Lick Observatory. The group photo (page 44) was taken toward the end of the construction period. When the 36-inch lens was finally mounted on the telescope, Floyd, Keeler, Alvan G. Clark, who had figured the lens, and Ambrose Swasey, whose firm had built the mounting, were the first to get a look at a star through it on a cold wintry night in January 1888. Just a few days later, on a night of exceptionally good "seeing" (good atmospheric definition) Keeler discovered a new, very fine division in Saturn's outer ring, the first discovery made with the new telescope.[7]

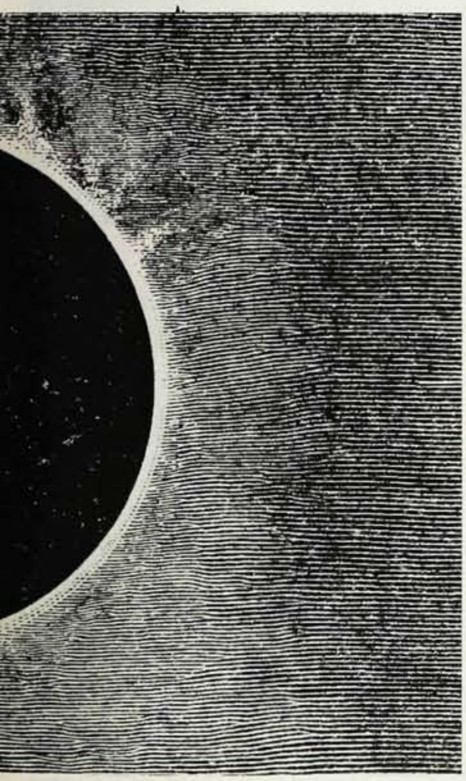
The Observatory was formally turned over to the University of California on 27 June 1888, and Holden became Director. He had assembled a small but excellent staff of whom only Keeler had any real training in physics. Holden himself and John M. Schaeberle had had good undergraduate educations in the traditional astronomy of position and orbit determinations, while S. W. Burnham and E. E. Barnard were keen-eyed visual observers with no formal scientific education of any kind. Keeler's first task was to design a spectroscope, which was built by his friend John Brashear at his instrument shop back in Pittsburgh. It was a visual spectroscope, made so that it would be used either with one of several prisms or with a Rowland grating as the dispersing element. Keeler understood the advantages of a large-aperture spectroscope, and the necessity of making the instrument as rigid as possible, so that accurate measurements could be made in any position of the 36-inch refractor.[8]

At the telescope, Keeler demonstrated his skill in visual observations. His ability to recognize small differences of contrast and color combined with his skill as a draftsman enabled him to produce excellent drawings of the planets, showing their visible features precisely and clearly. These pictures, particularly his drawings of Jupiter (page 45), were greatly admired and widely reproduced.[9] At the same time Keeler began using the spectroscope to examine the spectra of the major planets. He measured the wavelengths of the absorption bands in the spectrum of Uranus, and showed that the strongest of them were the same bands long known in Jupiter and Saturn, bands we now know to be due to CH_4. He correctly reported that they increase regularly in strength in the planets from Jupiter outward, and he was able to see the strongest band even in faint Neptune.[10]





In addition, Keeler also looked at the spectra of many stars, particularly those with bright emission lines. He made a long series of observations of the variable star β Lyrae and saw that it exhibited an emission spectrum containing not only hydrogen lines but also the line D_3, which until then had only been seen in the solar chromosphere and prominences. (It was



Keeler's drawing of the eclipsed Sun, 29 July 1878 (left). It shows prominences and the faint corona, which is the elliptical shape extended in the equatorial plane of the Sun. From US Naval Observatory Publications, 1880.

Samuel P. Langley, Director of Allegheny Observatory 1867–91, Secretary of the Smithsonian Institution 1887–1906 (above, left). This picture was taken in 1879, two years before the Mount Whitney expedition, during which he and Keeler made careful measurements of the solar spectrum. (Lick Observatory Archives.)

Keeler adjusting equipment for sending time signals from Lick observatory. This picture probably dates from 1886, shortly after he arrived at Lick to assist in its completion. (Lick Observatory Archives.)

first observed by the French astronomer Jules Janssen during the 1868 eclipse. A few years later the English spectroscopist Norman Lockyer and chemist Edward Frankland attributed this line to a new element, which they called helium.)

Keeler carefully measured a narrow absorption line seen on the broad D_3 and suggested it might be the same line, as in fact it is, but he could not bring himself to accept this interpretation.[11] He saw and clearly stated that the variations in the spectra were correlated with the light variations, but in a way that could not be due to simple eclipse effects, thus opening up the whole field of gas streams, disks and rings in binary stars, which has been the subject of so much research in the past 50 years. Keeler also observed the complex line profiles in the emission-line star P Cygni, and wrote that they could not be due to orbital motion alone, but must require some more complicated explanation.[12] Today we know that the explanation is mass loss from the star.

Keeler's outstanding achievement of this period was his accurate measurement of the wavelength of the two strong green emission lines observed in all gaseous nebulae.[13] Lockyer believed that the brighter of the two, the "chief nebular line," was due to a "magnesium fluting" (a band head of MgO), which fitted his meteoritic theory of nebulae, while his rival William Huggins maintained that there was too large a wavelength discrepancy for this identification to be correct. Keeler soon realized that with his large telescope, and the clear California atmosphere, he could make measurements far superior to those of Lockyer, Huggins or indeed anyone outside Lick. He could obtain very high dispersion with his Rowland grating, without weakening the light, since it is concentrated in a few emission lines. He was able to measure the wavelengths of the nebular lines with a precision of a few hundredths of an angstrom, while previously Lockyer had considered 1.5 Å an acceptable error.

Keeler quickly discovered that the nebular lines had slightly different wavelengths in different nebulae, which he attributed to the Doppler effect and to differences in the speeds of nebulae. He was able to measure the wavelength of Hβ and thus the radial velocities in a few of these nebulae; then correcting for the Doppler effect he obtained the rest wavelengths of the two nebular lines. The values Keeler measured, corrected to the modern MIT scale, are on the average within 0.05 Å of the best available values we know today. He found that the wavelength of the chief nebular line differed by over 0.4 Å from the nearest MgO feature, and thus conclusively ruled out this possible identification. Furthermore, from his accurate measurements he was able to conclude that neither of the two strong nebular lines coincided in wavelength with strong spectral lines of any known terrestrial substances. Keeler's drawing of the spectral regions of the lines are shown on page 48. Thirty-three years later I. S. Bowen identified these two green lines as forbidden lines of O^{++}, finally ending a long-standing astronomical puzzle.

While he was determining the nebular wavelengths, Keeler was also measuring very accurately the radial velocities of three bright stars with strong Na D absorption lines in their spectra. He checked and confirmed the whole method of spectroscopic velocity determinations by frequently measuring the Doppler effect in the spectrum of Venus, whose velocities with respect to the Sun and the Earth are very well known from orbital data. In this way he showed that his measurements had an accuracy of approximately 5 km/sec, far superior to any previous visual spectroscopic work.

At the same time as he was doing these pioneering spectroscopic measurements with the big telescope, Keeler was thinking seriously of leaving Lick Observatory.

A group of visitors and staff at Lick Observatory, August 1886. Back row, from left, Captain R. S. Floyd, an unidentified man, Thomas Fraser (construction superintendent), Mrs Cora Floyd, Keeler, G. C. Comstock, Cora Matthews (later Mrs Keeler). Front row, C. M. Plum and E. B. Mastick (Lick Trustees), E. W. Hilgard, (Berkeley professor), E. S. Holden, Harry Floyd (the Floyds' daughter). (From Lick Observatory Archives.)

He was in love with Cora Matthews, the niece of his old friend, Captain Floyd, and he did not consider the spartan living conditions in Mount Hamilton adequate for her or the family life he envisaged. He probably was also beginning to chafe under the directorship of Holden, although he never admitted this in writing. Keeler had kept good contacts in Pittsburgh, and he knew that Langley had been appointed Secretary of the Smithsonian Institution in 1887, was spending increasing amounts of time in Washington and was expected to resign his directorship at Allegheny Observatory in the near future. In the summer of 1890 Keeler wrote to Brashear, indicating diplomatically that he was available for the job as Langley's successor.

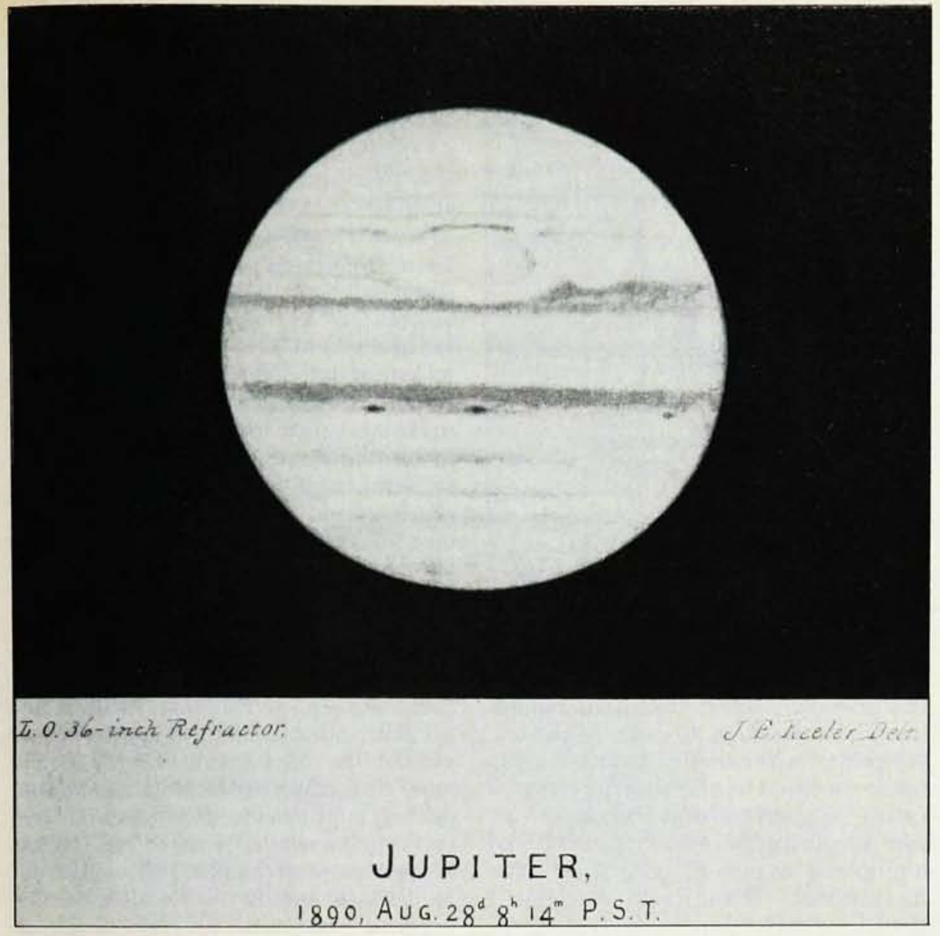
Return to Allegheny

He returned East for the first time in five years over Christmas 1890, and used the opportunity to solidify his contacts in Pittsburgh. In the spring of 1891, as a result of strenuous activity by Brashear (chairman of the Observatory Committee) Keeler was appointed Director of Allegheny Observatory. He and Cora Matthews were married at her parent's home in Louisiana on 16 June 1891, and by 7 July they were in Pittsburgh, where he immediately began work.

Allegheny Observatory was only sparsely equipped, and indeed Langley had taken much of the apparatus he used in his own research with him to Washington, regarding it as property of the Thaw family, rather than of the observatory. The Allegheny telescope, which had been used only infrequently by Langley in his later years, was a 13-inch refractor, pitifully small in comparison with the 36-inch Lick telescope that Keeler had given up. Mrs Thaw, the widow of Langley's patron who had provided the funds for Keeler's year in Germany, now promised the money for a new spectroscope. Photography was just then supplanting the human eye as a means of recording astronomical spectra, and Keeler designed the spectroscope to be an efficient but highly rigid instrument to minimize flexure in long exposures. Brashear built it, and they had it in operation on the telescope within a year. While waiting for its completion, Keeler wrote up for publication his Lick Observatory observational results on nebulae.

He also published an extremely interesting review paper, the substance of a semipopular lecture on the nebular hypothesis that he had given to the Pittsburgh Academy of Science and Art. He showed a recent photograph, taken by his friend Barnard at Lick Observatory, of the Andromeda Nebula, or Galaxy as we now call it, and correctly described how the stars in it are arranged in the same spiral pattern as the dark lanes. He told of the unsuccessful attempts to analyze its very faint spectrum. Then he passed to a description of the Orion Nebula, clearly shown spectroscopically to be composed of hot, low-density gas, compared it with planetary nebulae, and outlined the idea that all stars are formed by condensation of nebular material. Since the Sun is a star it must have formed in this way, along with the planets, and he sketched the regularities in the solar system and how they could have arisen in a rotating, contracting gas mass. Because the only possible energy source for the Sun known to the physicists of his time was gravitational contraction, he incorrectly gave 10^7 years as the lifetime of the Sun, but correctly concluded that "something unseen by our imperfect vision may intervene to avert this dismal end." Many of the ideas in this paper were well known to astronomers of the time, but Keeler put them all together and linked them to observational facts in a strikingly modern way.[14]

When his spectroscope was completed, Keeler began observing stars and nebulae, as well as comets whenever a bright one was available. Working photographically, he could record much fainter spec-



Jupiter, showing the Great Red Spot, equatorial belts, streamers, and small dark spots. This particular drawing, one of several done by Keeler at Lick, was widely admired and was reproduced in Century Magazine, July 1895 to illustrate a popular article. (Lick Observatory Archives.)

tra with the Allegheny telescope than he had been able to measure visually with the big Lick telescope, and he determined wavelengths of the fainter emission lines in the Orion Nebula.[15] He showed that many of these same lines occurred in absorption in the "Orion" stars; they were shown a few years later by William Ramsay, William Crookes, Friedrich Paschen and Hale to be due to helium. Keeler was doing very good work with the small Allegheny telescope, but his friend and former assistant, W. W. Campbell, who had been appointed in Keeler's old job at Lick, was providing increasing competition on spectroscopic measurements of nebulae and emission-line stars.[16]

Keeler's outstanding observational result at Allegheny was the confirmation that the rings of Saturn are composed of millions of small particles, each in its individual circular orbit around the planet.[17] In a classic paper in 1859, Maxwell had proved mathematically that the rings could not be stable if they were solid or liquid, and therefore that they must be composed of large numbers of independent particles. This result was widely accepted, but no one had subjected it to a direct observational test before Keeler. His spectra, taken with the slit of the spectroscope perpendicular to the rotation axis of Saturn (page 48), showed inclined lines in the main body of the planet, indicating rigid-body rotation, but the lines in the rings were inclined slightly in the opposite direction, indicating the expected outward decrease in orbital velocity. Since all the light observed is reflected sunlight, the Doppler shifts are approximately twice as large as they would be if the planet and ring were self-luminous. Keeler's measurements of the spectra showed that the inclination of the lines in the planet agreed with the known rotation period of Saturn, that the velocity at the midpoint of the rings agreed with the known mass of Saturn (from its satellites), and that there was a slight outward decrease in velocity in the rings, in agreement with the Keplerian formula. This simple but unquestionable demonstration of the nature of Saturn's rings, which was quickly confirmed by Campbell at Lick and by Deslandres in France, together with Keeler's earlier nebular work, made him the best known spectroscopist of his day; this work was the basis for the Rumford and Draper medals he was awarded by the American Academy of Arts and Sciences and the National Academy of Sciences a few years later.

The Astrophysical Journal

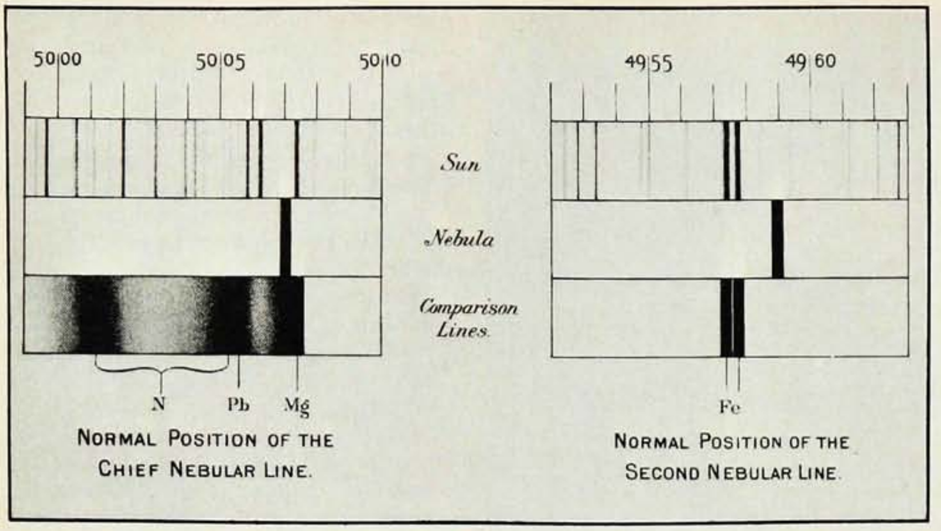
When George Ellery Hale, who was then 24 years old, founded the journal *Astronomy and Astro-physics* in 1892, he considered it essential to have Keeler as one of the associate editors. Keeler at first tried to beg off, but Hale wrote him in his characteristic fashion:

> "I shall be very greatly disappointed if you do not help me out in this matter, for I have really counted more on you than on all the others together . . . . If you do not agree to help me I shall be greatly inclined to give up my whole scheme of associate editors, and this would keep the journal where it is, and thus injure it. I know that you will be willing to aid the progress of science in this easy way, for there is no question that a journal of the highest class assists very materially in advancing the science which it represents."

Keeler agreed, and soon found himself aiding the progress of science in a harder way than he had bargained for. Hale, after persuading Charles T. Yerkes to provide the money to build a telescope even larger than the Lick refractor, decided to go abroad for a year to learn a little more astronomy before assuming the new observatory's directorship.[18] While Hale was in Europe, Keeler was left in charge of the journal, and in 1895, when *Popular Astronomy* was split off, Hale and Keeler together became the founding editors of the *Astro-physical Journal*, as it has proclaimed on its masthead ever since.

Keeler was the expert consultant chosen to make the acceptance tests on the 40-inch lens for the new telescope at the "optical factory" of Alvan Clark and Sons, where it had been ground and polished, and he was also the main speaker at the dedication of Yerkes Observatory in 1897. His talk, "The Importance of Astrophysical Research and the Relation of Astrophysics to Other Physical Sciences" was a forward-looking call to study the composition, physical conditions, motions, distances and evolution of the stars by the new methods of astronomical spectroscopy. Hale tried to hire Keeler as an assistant director at Yerkes, to be in charge of stellar and nebular astrophysics. Keeler, however declined the offer to move to Wisconsin, and instead returned to Lick as director in 1898.

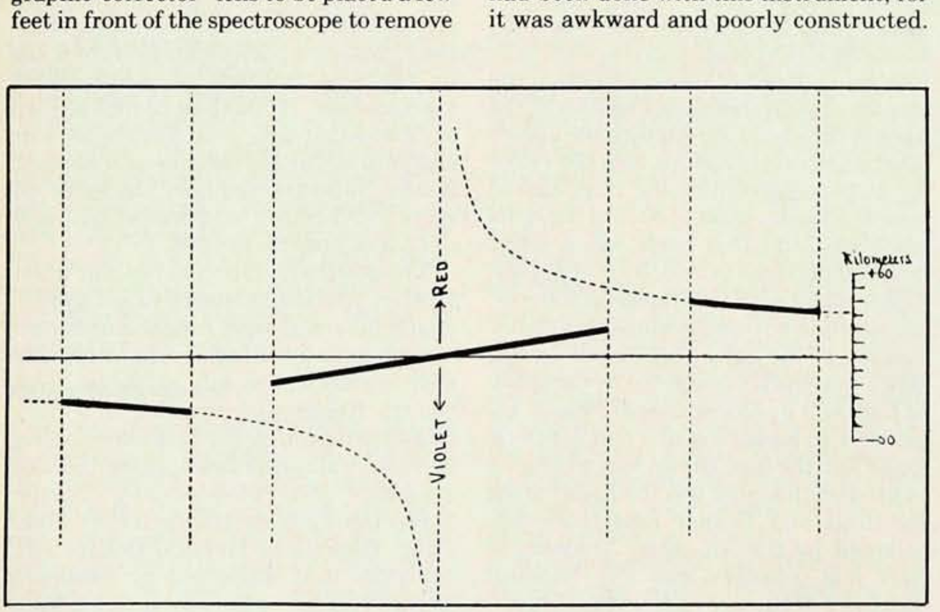
The position had become vacant when Holden, who had managed to antagonize nearly his entire staff, resigned under severe pressure just a few days before Keeler gave the dedication talk at Yerkes. Although Keeler was regarded as a dark horse for the job by the Lick astronomers and the California newspapers, he was strongly recommended by Simon Newcomb, Langley, Hale and E. C. Pickering, Director of Harvard College Observatory, was supported by President Martin Kellogg of the University of California, and was elected by the Regents in a public meeting carried out and reported in the newspapers much like a political convention.



Keeler's drawing of nebular spectra including the two principal nebular lines and the comparison lines he used to determine their wavelengths. The terminal line of the magnesium fluting (MgO band head) is also shown at its measured wavelength in the left part of the figure. It is clearly some distance away from the principal nebular line. From Lick Observatory Publications, 1894.

Keeler had for many years been troubled by the inefficiency of refracting telescopes. The lens of his Allegheny refractor had become yellow with age and transmitted very little of the blue and violet light to which the photographic plates of those days were sensitive; Keeler had managed to get the spectra of Saturn's rings only by using the very new orthochromatic (yellow-sensitive) plates, and at the time he left Allegheny he was taking his pioneering spectra of "third-type" (cool) stars on panchromatic plates.[20] Since refractors were designed and figured as visual telescopes, the yellow light was in focus on the slit of the spectroscope but the photographically active blue light was badly affected by chromatic aberration and much of it was wasted. Keeler had designed a "photographic-corrector" lens to be placed a few feet in front of the spectroscope to remove this problem,[21] a partial solution that has since been used on all large refractors. Nevertheless he believed that a reflecting telescope would be a far superior research instrument and had drawn up plans for a new Allegheny Observatory, built around a proposed 30-inch reflector to be made by Brashear. When Keeler was offered the Lick directorship, he delayed acceptance, and said he would stay at Pittsburgh if the money could be raised for this new observatory, but the whirlwind fund-raising campaign failed.

Lick Observatory had a reflecting telescope, a 36-inch instrument that had belonged to Edward Crossley, a wealthy British amateur astronomer. When he tired of it, he tried to sell the telescope, but was persuaded by Holden to give it to Lick in 1895. No serious research work had been done with this instrument, for it was awkward and poorly constructed.



Keeler's drawing of the Doppler effect in the spectrum of Saturn. The slit of the spectrograph was aligned along the major axis of the planet and the rings. The spectral lines then have the shape shown in the graph, which shows the average from a number of measurements. The body of the planet rotates as a rigid body, but particles in the ring are in Keplerian motion. From ref 17.

When Holden assigned staff member W. J. Hussey to bring the Crossley into operating condition and use it, he refused, saying he had been hired to work with the 36-inch refractor and had no time to waste on the reflector. This quarrel was one of the precipitating events of the final struggle that led to Holden's ouster. Most of Keeler's previous research had been in spectroscopy, but he knew that Campbell had taken charge of this work at Lick, and had become one of the leaders in the field. He would not be happy to give it up. Hence, on his arrival at Mount Hamilton in June 1898, Keeler made everyone happy by announcing that he himself would take over the Crossley reflector (page 40) and would devote his own personal research efforts to it. He also set up three Lick Observatory Fellowships, making it possible for graduate students to work at Mount Hamilton, dividing their time between research there and taking courses in Berkeley.

Keeler threw himself into the Crossley problem, using all his practical mechanical skill and astronomical experience to rebuild the drive, make the telescope more rigid, improve the plateholders and guiding mechanisms, and in general convert it into a reliable research instrument. Helped by two of the Lick Fellows, Harold K. Palmer and E. A. Coddington, he began a systematic program of direct photography of nebulae. Because of its short focal ratio ($f/5.8$), achromatic property and lack of absorption, the Crossley was relatively fast, and Keeler's plates showed much more faint detail than anyone had previously seen. Nebular photography had previously been done by Isaac Roberts in England, but the larger scale of the Crossley combined with the clear sky and excellent seeing on Mount Hamilton helped Keeler open a new world of study. He confirmed the existence of structures in planetary nebulae that a few visual observers had previously suspected, but that most had doubted. By comparing photographs of the Orion Nebula taken through different color filters, Keeler discovered that the green nebular-line emission is more strongly concentrated to the stars in the central, brightest part of the nebula than the Hβ emission is. In arcs and streamers near some of the outlying stars, the green lines are quite weak, although Hβ is very strong.[22] Keeler was uncovering many clues which, if he had had more time left to follow them up, would probably have led him to an understanding of the input of energy to nebulae from their associated stars.

His greatest discovery, however, was the existence of very many small, faint nebulae far from the Milky Way. He found that on every long-exposure plate he took with the Crossley reflector, he could see many previously unknown small nebulae. Most of them were spirals, thin flat disks seen in every projection from face-on to edge-on. The Andromeda Nebula was but the largest example of a class of objects that occur over and over again in the sky, down to the smallest nebulae he could resolve with the Crossley. He estimated, from the small fraction of the sky that he had sampled, that the total number of spirals within reach of the Crossley was at least 120 000. He reasoned that their spiral forms probably resulted from rotation, and that differences in the amounts of rotation probably caused the observed differences in the forms of the small nebulae.[23] He emphasized the beautiful, complex structure of spiral nebulae, and that they did not have the simple forms of rotating fluid bodies obtained mathematically by Henri Poincaré. Keeler was pioneering in observational research on galaxies, except that he did not realize that the "small nebulae" were in fact star systems. Keeler had a small, low-dispersion spectrograph under construction in the observatory shop, that would undoubtedly have helped him unravel the mystery of the composition of the spirals. But in the summer of 1900 Keeler, who had been working very hard, contracted a cold he could not throw off. He left Mount Hamilton with his family to recuperate at Captain Floyd's Clear Lake estate, now owned by Floyd's daughter. Keeler's condition became worse, and he entered a hospital in San Francisco, where his trouble was diagnosed as a heart condition. He died of a stroke a few days later, on 12 August 1900.

Keeler was not quite 43 years old when he died, but he had pioneered in applying astrophysical methods to analyzing the nature of planets, stars and nebulae. He made outstanding discoveries in all these fields himself, and pointed the way for future generations of astronomers. All large telescopes built after his work with the Crossley were reflectors, rather than refractors as in the past. It was only through the work of Hubble after World War I that the small nebulae were established as galaxies, but Keeler's research in the late 1890's paved the way for this result and would have led further toward it if he had not died when he did. From his early days with Langley working on infrared astronomy, to the end of his life at Lick trying to understand the nature of the small nebulae, he was doing frontier research on problems we still work on today.

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No full-length biography of Keeler exists yet; I am working on one at the present time. There are biographical sketches of him by his colleagues W. W. Campbell, Astrophys J. **12**, 239 (1900); C. D. Perrine, Pop. Astron. **8**, 409 (1900); J. A. Brashear, Pop. Astron. **8**, 476 (1900), and C. S. Hastings, Bio. Mem. Nat. Acad. Sci. **5**, 231 (1903). The primary sources of biographical information on Keller are the correspondence and newspaper clippings in the Lick Observatory Archives at the University of California, Santa Cruz, and in the Allegheny Observatory Archives at the Hillman Library of the University of Pittsburgh. Smaller collections of materials relating to Keeler are in the Bancroft Library at the University of California, Berkeley, and the Milton S. Eisenhower Library and the Ferdinand Hamburger, Jr Archives at Johns Hopkins University. I would much appreciate being informed of any other existing correspondence regarding Keeler.

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