THE SCIENTIFIC CAREER OF JESSE L. GREENSTEIN

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ABSTRACT. The scientific career of Dr. Jesse L. Greenstein covers nearly 60 years, a thousand nights on various telescopes, and several hundred papers. He has made substantial contributions in a number of major research areas including interstellar work, stellar abundances and nucleosynthesis, faint blue stars, white dwarf stars, comets, and quasars. He has combined productive research with distinguished service to our profession in a truly exemplary manner.

1. INTRODUCTION

I am delighted to present the scientific work of Jesse L. Greenstein, to whom this Symposium is dedicated. His extraordinary carrer is spread over nearly 60 years and has been very prolific. He has an average of $8\frac{1}{2}$ papers published per year throughout his career. Even now that he has retired he keeps up this rate: 9 papers in 1984, 8 in 1985, 6 in 1986. When Greenstein was 8 years old his grandfather gave him a brass telescope and he delivered lectures to his friends on astronomical topics from planets to nebulae. Later he had a basement lab complete with prism spectroscope and arc and tried to identify atomic lines – portents of things to come... His favorite subjects in high school were Latin and chemistry; he admits to finding high school physics to be dull. He entered Harvard by age 15, received his A. B. degree in 1929 and his Master's degree in 1930. He was expected to go into the family business, and so he did. However, he did *volunteer* work at Columbia University where he searched for RR Lyr variables in M 3 and produced light curves for 199 stars. Although he found the work monotonous, he knew he preferred to pursue graduate work in astronomy rather than to remain in business. He returned to Harvard in 1934 for his Ph. D. studies, undiscouraged by Shapley's remarks that the science had progressed too rapidly in those 5 years for him to be able to catch up. After his Ph. D. in 1937 from Harvard, he received a National Research Council Fellowship for 1937–1939 and went to Yerkes Observatory where he stayed on until 1948. The development of Palomar Observatory brought him to the California Institute of Technology in Pasadena in the leadership role in the pursuit of astronomical frontiers for Caltech. He built the Caltech Astonomy Department into the premier astronomy department in the United States and has stayed there through and beyond his formal retirement in 1980; he remains active as the Lee A. DuBridge Professor of Astrophysics, Emeritus.

2. INTERSTELLAR WORK

His first paper (1930), written when he was still an undergraduate at Harvard University, was on the colors of B stars. It deals essentially with the then still unrealized effects of interstellar reddening. His Ph.D. thesis work at Harvard was with Bart J. Bok, observing the spectrophotometric differences between reddened and unreddened B stars. He established that the absorption varied as $\approx \lambda^{-0.7}$ and determined the ratio of photographic absorption to reddening (on the International scale) as ≈ 4. He interpreted this by computation of the extinction coefficient of small particles from the theory of Gustav Mie. The extinction was found to arise from dielectric grains with a power-law mixture of sizes and a high albedo. Earlier pioneers in the study of dust had been Schönberg and Jung, in Germany, Schalèn in Sweden, who were interested in metallic grains.

After his Ph. D. work, he was able to obtain a National Research Council Fellowship, one of the few available in physical sciences, and chose to go to Yerkes Observatory of the University of Chicago in Williams Bay, Wisconsin. He had first learned atomic spectroscopy and the theory of emission lines in ionized gases from Donald H. Menzel. At Yerkes he came under the powerful influence of the Director, Otto Struve, who had invited Jesse to come there. At Yerkes from 1937–1948, he at first continued new studies of interstellar matter. In 1938 the invention of the nebular spectrograph, a highly efficient low-dispersion instrument permitted him to study the spectra and colors of reflection nebulae, of extended emission nebulae of low surface brightness and of comets. Among the most important results of collaboration with Louis Henyey on the theory of radiation transfer in dust clouds was the discovery of diffuse galactic light, dust scattering of starlight in the Milky Way. They also established the phase-function and high albedo of dust in reflection nebulae, confirming that the grains are ices of frozen gases and relatively non-absorbing silicates, rather than metallic compounds. Bengt Strömgren, with Struve and C. T. Elvey, found the diffuse line emission of Hα to be generally present in the Milky Way; Strömgren soon developed the beautiful theory of H II regions, beginning the modern physics of interstellar matter, with hydrogen the dominant constituent.

Only much later did Greenstein return to the theory of interstellar dust after interstellar polarization was discovered by W. A. Hiltner and J. S. Hall. At Caltech, after 1948, he worked with the theoretical physicist Leverett Davis. This pioneering work, referred to as the Davis–Greenstein mechanism in graduate astronomy textbooks, is still valid in large part. They devised a very elaborate theory (1951) of the interaction between spinning, non-spherical, dust grains and interstellar magnetic fields, which align the grains with their long axis perpendicular to lines of force. Since the polarization vectors had been observed to be parallel over large stretches of galactic latitude, the magnetic field lines were along spiral arms. The Davis-Greenstein mechanism requires dissipation of the spin energy within the grains, through the complex part of the paramagnetism. Although the magnetic fields required (about 30 microgauss) were larger than eventually observed from Zeeman splitting of the 21-cm line, the basic physical mechanism of grain alignment is correct.

After significant contributions to the study of interstellar matter, he switched his astrophysical interests to a completely different subject, the study of stellar spectra at high resolution (for those days). It is characteristic of his career that he explored new specialities, both to learn new astronomy and its related physics and to make use of newly available equipment on new types of objects.

3. STELLAR SPECTRA, ABUNDANCES, NUCLEOSYNTHESIS

Greenstein started in this new scientific direction, stellar spectroscopy, while he was still at Yerkes. In this he was much influenced by Struve and by Pol Swings (from Liège), a visitor to Yerkes just before the outbreak of WW II. The 82-inch reflector at the McDonald Obervatory of the University of Texas was designed and operated by the Yerkes Observatory. Dedicated in 1939, it had an excellent ultraviolet 3-prism cassegrain spectrograph; its coudé, with Littrow prisms, had dispersion of 2.5 Å mm^{-1} at $H\gamma$. Simultaneously, Theodore Dunham was building new, improved coudé grating spectrographs with schmidt optics for Mount Wilson. The astrophysical interests of Struve, Swings and Unsöld (also a visitor in 1939), gave spectroscopy at McDonald an especially modern innovative flavor. Struve told Greenstein, who was to be one of the first observers at McDonald, that he might consider studying υ Sgr. He did, with fascination; its spectrum was extraordinarily interesting, dominated by ionized metals and neutral helium, lacking Balmer lines and jump. It was a helium-rich star; Greenstein's pioneering analysis in 1940 is second only to Louis Berman's 1935 study of R CrB. The latter is rich in carbon, and was eventually found to have a helium chromosphere. Stars with both composition and opacity dominated by helium could not provide absolute abundances in those primitive days. Good opacities, model atmospheres, line-broadening theory and transition probabilities for most of the lines were non-existent. Comparisons were made with the sun. But his studies of υ Sgr gave some ideas of composition; He was high and N I and Ne I were strong. The star later showed line-profile variations, and evanescent $H\alpha$, material presumably from the invisible companion. In the same observing run excellent coudé spectra of the B star, τ Sco, were obtained on high-contrast films for Unsöld, who used them for the first, modern quantitative analysis of H, He, C, N, O, Si. Several of Unsöld's students at Kiel re-analyzed these spectra with progressively better models, line-broadening theory and transition probabilities, beginning the trend to "fein-analyse" of the stars.

Greenstein (1942) next observed the bright giant α Car, so far south as to strain the pointing capability of the 82-inch. He used what Unsöld would have called a "grob-analyse" method, with a curve of growth; the main difficulties were in the lack of knowledge of f-values. He used LS-coupling transition arrays and empirical solar transition probabilities, which were then being derived by Menzel and Goldberg. Without stellar models, it was necessary to use different excitation and ionization temperatures. Abundance ratios relative to the Sun were normal in α Car. Following this general, but improving methodology, many stars were analyzed. Among the first was the metallic-line star, τ UMa, which showed numerous abundance deficiencies (notably Ca) as well as excesses; some of these anomalies were ascribed to non-LTE ionization. Greenstein thus initiated a series of coudé analyses of stars using the differential curve of growth method. K. O. Wright independently developed the method of differential curve of growth analysis in Canada. Collaborative efforts established generally useful techniques of calibrating plates and standard equivalent widths in stars.

World War II interrupted research at Yerkes and McDonald; immediately afterwards, opportunities blossomed. The 200-inch mirror was approaching completion when, in 1948, Greenstein left Yerkes to set up a department and assemble a new staff for the California Institute of Technology and its Palomar Observatory. The Mount Wilson and Palomar Observatories were jointly operated with remarkable resources. High-resolution spectroscopy, first of the Sun, and then the stars was a specialty of the older Mount Wilson staff. Paul Merrill discovered technetium in S stars soon after the first laboratory spectroscopy of that unstable element. Greenstein brought a more quantitative, astrophysical approach, and extended the work to intrinsically fainter stars. An interesting new topic was study of the light elements, subject to nuclear reactions at relatively low temperatures. The physicists of the Kellogg Radiation Laboratory specialized in energy levels and reaction rates of these relatively simple nuclei; Charles C. Lauritsen and William A. Fowler were interested in the astrophysical applications, notably energy generation. Greenstein worked on the changes in abundances produced by such reactions, devising astronomical tests; with collaborators, he searched for Li in the Sun, and the $^6Li/^7Li$ ratio. In the far ultraviolet region he looked for Be, neutral and ionized; B was inaccessible in the far ultraviolet. Lithium was depleted showing that solar surface material had mixed down into the envelope reaching above 10^6 K. Such solar spectroscopy, at least, qualifies for the subject of this conference, high S/N. Fred Hoyle had proposed that elements were synthesized in stellar interiors. Large He/C or C/H in evolved stars, high $^{13}C/^{12}C$ ratios, unstable Tc, elements with large neutron excesses such as rare earths and uranium, combined with the expanding knowledge of reaction rates all suggest the generalization that all elements heavier than He were synthesized in stellar interiors. Greenstein was active, pushing astronomical observations of these rare elements to compare with critical nuclear predictions; his first review of this comparison was at Utrecht in 1952. The elements Li, Be, B are not produced in stellar interiors, but by spallation by cosmic rays, according to Fowler, Greenstein and Hoyle. Energetics permit the process $^{13}C +^4 He$ to yield a neutron for each ^{13}C nucleus in red giants, thus leading to heavy elements in S stars. The theory of stellar nucleosynthesis culminates in the Burbidge, Burbidge, Fowler and Hoyle paper in *Reviews of Modern Physics* (1957).

From 1957 to 1970 Greenstein ran an "Abundance Project," under which numerous postdoctoral fellows came to Caltech from all over the world to use the Mount Wilson and Palomar telescopes and spectra. They produced, for the first time, a large number of quantitative studies of stellar composition. Many of those visitors have now become leaders in the field, including our hostess, Giusa de Strobel Cayrel. Some analyses were based on the differential curve-of-growth method, others used early model atmospheres. While few of the photographic spectra used would now qualify as having high signal-to-noise ratio, they were at high dispersion, with good instruments. They provided important information and tests of the new theory of stellar nucleosynthesis in the 1950's.

The composition of the oldest stars, born soon after the Galaxy formed, has great evolutionary significance. The metal deficiency of the unevolved sdG's was first determined by Aller and collaborators, including Greenstein; the weakness of the metallic lines is partly compensated for by the relative simplicity of the spectrum and ease of location of the continuum. Some abnormal ratios of heavy elements to Fe were suspected, and the abundances of C, N, O became targets of various investigations. A few, very long Palomar exposures, (up to parts of three nights), gave spectra of individual stars in globular clusters at 18 Å mm^{-1}. Similar halo giants were found among field stars, notably HD 122563, which was analyzed several times with more refined methods. The heavier elements appeared to have lower ratios to Fe in the most metal-deficient stars. Higher ratios were ascribed to nuclei containing integral numbers of α particles. An interesting observation was the 6300 Å line of [O I] in K giants at the highest possible signal to noise. Giusa and Roger Cayrel worked with the best possible data for ϵ Vir; they also provided tables facilitating relative analyses, allowing for different stratification depending on temperature and gravity, in model atmospheres with a "scaled" temperature distribution. Later, as a result of the accumulation of numerous abundance analyses, George Wallerstein found the useful correlation between ultraviolet excess, $\delta(U-B)$, and the metal deficiency $[Fe/H]$.

4. COMETS

Another field captured Greenstein's attention: during the 1950's there were several bright comets. So he used the new coudé facilities to obtain excellent spectra of Mrkos, Arend-Roland, Ikeya and Humason (which had unusually strong CO^+) . The high resolution made possible detailed study of the intensity of the rotational lines, as well as their variation in the inner coma. The Swings excitation mechanism depends on the flux in the solar spectrum as seen velocity-shifted to the comet's rest frame; large intensity differences occurred between successive rotational lines, depending on the details of the solar line absorptions. Greenstein discovered a new phenomenon: changes of intensity of a rotational line along the slit, on opposite sides of the nucleus. Now called the "Greenstein effect" by cometary scientists, the phenomenon arises from internal motions of the cometary gas (probably from rotation of the nucleus) which shift the absorption of the molecules. This rotation was confirmed in the recent flybys of Halley. The Na emission was asymmetric with respect to the nucleus. An attempt at the cometary isotope ratio, $^{13}CN/^{12}CN$ was possibly vitiated by an overlapping NH_2 blend.

5. FAINT BLUE STARS, WHITE DWARFS

When Greenstein was 60 he changed fields again. The challenge of the availability of the 200-inch Hale reflector lead him to transfer his efforts to intrinsically fainter hot stars, both the "faint blue stars" (FB) and white dwarfs (WD), abandoning high dispersion spectroscopy. Most are apparently faint, demanding lower spectroscopic resolution. Only the newer generation of photoelectric sensors, with interferometric or echelle spectrometers, makes high resolution and good signal to noise possible for fainter stars. The faint blue stars and white dwarfs were the subject of an IAU Colloquium at Tucson in June 1987, and are therefor less fully reviewed here. By 1958 it was clear that a variety of types of stars populated the lower-left-hand quadrant of the HR diagram; Guido Münch and Greenstein found that blue stars on the horizontal branch of globular clusters had weak He I lines, as did the halo sdB's. Sargent and Searle developed a rapid quantitative method to obtain gravity and temperature from UBV colors and the widths of the Balmer-line profiles based on the available LTE models. Baschek, Newell, Norris studied field and cluster FB's. Finally, in their extensive survey of FB stars, Greenstein and Anneila Sargent (1974) found the HBB and sdB stars to have constant $log\, g\theta^4$, which measures the M/L ratio. They derived the mass of the halo field stars as $0.56M_\odot$. Some FB's are apparently normal B's, with characteristics of population I, but at distances and travel times from the galactic plane exceeding their nuclear lifetimes. Most FB's have only slow rotation, and are highly evolved. Quantitative analysis has since revealed helium-rich, chemically-peculiar, often variable stars among the FB's. Convection, diffusion, radiation pressure and mixing complicate the subject. The Kiel group has been extensively observing the sdB, sdOB and sdO stars at ESO, with great success.

Observing high quality spectra of white dwarfs is not easy; they are faint and have weak lines at high (or low) temperature. Starting with stars selected by blue color and proper motion, Eggen and Greenstein (1965-67) confirmed and published colors and spectra of 200 WD's; in total, Greenstein spent about 300 nights with the 200-inch on this problem. He published data on 550 white dwarfs from the prime-focus spectrograph, Oke's multichannel spectrophotometer and the double CCD spectrograph (1965–1986). In 1983, after his retirement he observed 200 stars at 5 Å resolution in 8 nights; he could achieve signal-to-noise > 100 in 10 minutes for objects at $V = 16$. Some observations are high signal-to-noise spectroscopy, with counts $\approx 10^5$ in the low resolution multichannel photometry and with the CCD yielding 30000 photons per pixel; for example, a composite hydrogen-line profile in ten DA's is based on nearly 10^6 detected photons. High S/N is essential to reveal the weak, shallow and very diffuse absorptions found (1986) in the strongly magnetic WD Grw +70°8247; four had been found (1957) by superposition of tracings of numerous photographic spectra. These are Zeeman components of Hα, Hβ and Hγ in a 350 megagauss dipole field. By superposition of photographic spectra he discovered and first identified a band of C_2 200 Å wide and 10 % deep in a carbon-rich WD. Quantitive analyses of composition of WD's with metallic lines were carried out first by Weidemann on van Maanen 2, and in others by Greenstein and his collaborators. Spectroscopy of the ultraviolet with IUE has become possible; it provided a confirmation of the ground-based temperature scale, and also revealed an unidentified broad feature at 1400Å. Koester and Weidemann later identified it as a quasi-molecular transition in H_2. The extraordinary transparency of an atmosphere dominated by helium made it possible to detect metals even when they were 10^{-5} or less as abundant as in the sun; the same is true in the few WD's showing carbon.

A general picture of WD atmosphere emerged: the DA's have negligible helium and only rarely detectable metals. The non-DA's have negligible abundance of hydrogen, and often traces of carbon and metals. The WD's have very stable atmospheres, and the hydrogen even in DA's is concentrated in a surface layer of less than 10^{-5} M $_\odot$. The metals and helium diffuse rapidly downwards, and there may be some accretion (which should, magically, exclude hydrogen). Some pre-WD's may lose all their hydrogen, resulting in the non-DA's; alternatively convective mixing could dilute the residual hydrogen.

Greenstein's study of WD's over the years produced abundance analyses and extensive quantitative results on their physical state. A temperature scale came from fitting models to his spectrophotometry, with energy distributions and line profiles in both the hydrogen-rich and helium-rich degenerates. Results obtained from his extensive data include the fact that the HR diagram is narrow; parallaxes give the $\sigma(M_V) \approx \pm 0.3$ mag, i.e. only small range of radii and surface gravities. The WD's rotate only slowly (≤ 100 km s^{-1}); their red-giant predecessors have lost proportionally more of their angular momentum than mass. In a series of papers with Virginia Trimble and others, the Einstein gravitational redshift was found to agree with that expected from the mass-radius diagram with a C, He core. After the rapid variability of the ZZ Ceti type DA's was discovered, multichannel colors established that oscillations are confined to a narrow range of temperature.

6. RADIO ASTRONOMY

Greenstein had a long enthusiasm for radioastronomy; with F. L. Whipple he had written a premature theoretical explanation of Jansky's observations in 1937. In

1956 he helped organize the start of Caltech's radio observatory. Identification of many Cambridge 3C sources with active galaxies left unexplained some that remained unresolved by the best radio-interferometric measurements. These were identified with "blue stellar objects" as apparently stars with peculiar spectrum and colors, by A. R. Sandage and Tom Matthews; the accurate lunar-occultation position of 3C273 permitted Maarten Schmidt to identify it with a bright stellar object and recognize its redshift as 16 % . Greenstein had observed extensively weak emission lines in the fainter blue stellar object 3C48. When Schmidt discovered the redshift of 3C273, Greenstein immediately recognized that 3C48 was also redshifted, by 37 % . Greenstein and Schmidt (1964) analyzed the physical conditions in the line-emitting regions of these first two quasars recognized. The methodology was Menzel's for planetary nebulae but essential new concepts include the implausibility of a gravitational origin of the redshift, the high density from observed collisional de-excitation, line broadening by electron scattering, the spatial separation of the emission-line and radiofrequency emitting regions. The energy required to maintain the high luminosity at cosmological distances suggested that nuclear energy did not suffice. With the mystery of the central source energy source unsolved, Greenstein abandoned that field, happy that the cosmological redshift left an exciting difficult question for the next generation.

7. CONCLUDING REMARKS

During all this time, he served as department head for 24 years, observed over a thousand nights at large telescopes, and frequently advised the U.S. government on the requirements for financial support of astronomy. He served on some 50 important national and international committees on various aspects of astronomy. Among the most significant was his chairmanship of the "Greenstein Report," the study of the priorities and prices of *Astronomy and Astrophysics for the 1970s* for the National Academy of Sciences of the U.S.A. We retain his name on some of his discoveries: the Henyey-Greenstein camera, the Davis-Greenstein mechanism, the Greenstein effect.

Among many honors are the the California Scientist of the Year award (with Schmidt) for work on quasars, the Bruce Gold Medal of the Astronomical Society of the Pacific, the Gold Medal of the Royal Astronomical Society, NASA's Distinguished Public Service Medal and an honorary D. Sc. from the University of Arizona this June.

Having been named the Lee A. DuBridge Professor of Astrophysics in 1970, he retired to the Emeritus status of that Professorship in 1980; he stopped observing in 1983, but still works, currently on the molecules that may serve as population discriminants in M dwarfs. He is to be greatly revered for his significant scientific achievements and his distinguished professional service. Many of us here at this conference eagerly and fortunately learned much about stellar spectroscopy from Jesse Greenstein. His influence is far-reaching. It is a very fitting tribute to dedicate this Symposium to him.


THE DICKIES
Will Drive You Ape