Wallace L. W. Sargent

1935–2012

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
Charles C. Steidel

NATIONAL ACADEMY OF SCIENCES

WALLACE L. W. **SARGENT**

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By Charles C. Steidel

Wallace L. W. Sargent was the Ira S. Bowen Professor of Astronomy at the California Institute of Technology, where he was a member of the astronomy faculty for 46 years, beginning in 1966. By any measure, Sargent—known to colleagues and friends as "Wal"—was one of the most influential and consistently productive observational astronomers of the last 50 years. His impact on the field of astrophysics spanned a remarkably wide range of topics and was seminal in more than a few: the primordial helium abundance, young galaxies, galaxy dynamics, supermassive black holes, active galactic nuclei (AGN), and, particularly, the intergalactic medium (IGM). Wal was 77 at the time of his death in 2012; he had maintained a full complement of teaching and research until just weeks before succumbing to an illness he had borne quietly for more than 15 years. Generations of students, postdocs, and colleagues benefited from Wal's rare combination of scientific taste and intuition, intellectual interests extending far beyond science, irreverent sense of humor, and genuine concern about the well-being of younger scientists.

Education and Early Influences

Wal was born in 1935 in Elsham, Lincolnshire, United Kingdom—a small village roughly equidistant from Sheffield and Leeds in West Lincolnshire—into a working-class family. Neither of his parents had attended school beyond the age of fourteen. His father, Leslie, was stationed at an RAF air base near London during World War II, prior to which he had been a gardener working at a local estate; after the war, he worked in a local steel mill, the principal industry in the Scunthorpe area of North Lincolnshire. His mother, Eleanor, was a shop assistant and a domestic servant before marrying, and spent the war years cleaning the houses of the somewhat-better-off in the surrounding villages. The family, which included younger brother Gordon (born 1938), moved to nearby Winterton (population: ~ 5000), a few miles south of the Humber estuary in North

W.L.W. Sargent, 1941.

Lincolnshire, where Wal attendedprimary school from 1940– 46. Wal recalled his rather unusual educational path in an interview with Alan Lightman in 1998: at age eleven, all students in the primary school were given an exam to determine their post-primary destination. He was one of six students out of a class of forty-four to be selected to attend the local "technical school," which was midway between a grammar school—the destination of students on a purely academic track—and a "secondary modern" school, the destination for the 80 percent of students expected to finish their education by age fourteen. The Scunthorpe Technical High School existed to train local students for skilled work in the local steel mills (e.g., draftsmen). The normal educational path for British students intending to pursue post-secondary education was to begin a specialized course of study between age sixteen and eighteen, in preparation for admission to university. However, Wal had taken an unusually large number of "O-levels" (nine) at age sixteen, and did very well in all of them. These would normally have been taken for subjects in which a student intended to specialize in the final two years of secondary school prior to entering a university. But Wal was interested in, and proficient at, a broad range of subjects, including humanities, and Scunthorpe Technical School arranged for him—and a few other students who intended to be school teachers—for two years beyond the normal leaving time. From ages sixteen to eighteen, Wal pursued a largely self-directed curriculum that was broader than he would have experienced on a normal academic track, guided by his own wide interests and the ability of a teacher to supervise. Wal credited his pursuit of a liberal education to the constant encouragement of his mother who, in spite of her own limited education, had always insisted on its importance, and dreamed that Wal would attend university, particularly Oxford.[1] The support of his mother was strong even during the lean post-war years in Britain when an additional family income would have made a big difference; Wal remembered feeling guilty about staying in school when he could have been earning money by working.

Sargent continued his studies and prepared to apply to university, without the benefit of advice on how to do it, since he was the first student from Scunthorpe Technical High

1 Wal later speculated that Oxford may have been the only university whose name she knew, from having worked in a shop whose proprietor had a son who had gone there.

School ever to attend university of any kind, and the first in his family to attend school beyond age fourteen. During the years prior to university, Wal's ambitions were growing; initially, he hoped to become a draftsman at the local steel works, which he considered to be a "posh" job because it involved working in an office and wearing a tie. However, Wal cited the 1950 BBC Radio series "The Nature of the Universe," hosted by astronomer Fred Hoyle (FRS 1957; later Sir Fred Hoyle) as particularly influential on his developing interest in science. Hoyle's lucid explanations of the workings of scientific inference—for example, how one might infer underlying physical properties from apparently indirect observations—impressed the fifteen -year-old Sargent. Just as important for Wal, Hoyle spoke with a pronounced northern (Yorkshire) accent—almost unheard-of in the British media of the time—a fact that Sargent found inspirational because it made it seem possible that someone from the North could succeed in becoming a scientist.

In 1953, Wal matriculated at the University of Manchester (he did not end up applying to Oxford), attracted by their very strong physics department, where the last three professors had been Nobel Laureates (Rutherford, Bragg, Blackett), and by the Jodrell Bank (radio astronomy) Observatory, which had been established by Bernard Lovell in 1945 to investigate cosmic rays, after being used as a radar research facility during the war. As an undergraduate, Sargent studied physics, and at the end of his three years, he was awarded a fellowship for graduate study in an area of his choice. Undecided among several options, he finally chose theoretical astrophysics, in spite of his not having gone through the theoretical course in the last year of his undergraduate program. There was a lot of interesting work going on in Manchester at the time in fluid mechanics, and it occurred to Sargent that it might be applied to a problem in astrophysics. He began working with Franz Khan in his second year, and after a few false starts, he embarked on a project to work on the effect of supernova explosions on the surrounding interstellar gas (a topic that remains of considerable interest in 2019). But Khan was about to depart for a sabbatical year visiting Princeton and then Caltech, and so most of Wal's correspondence with his Ph.D. advisor was by letter. Khan's year in the United States caused Wal's Ph.D. thesis work to be carried out with more independence than might have been, but it led to a providential opportunity for Sargent post-Ph.D.

While visiting California, Khan met Jesse Greenstein, who had started the Caltech astronomy department a decade earlier in connection with the commissioning of the 200-inch Hale Observatory at Mount Palomar (1948). At the time, Greenstein was working on the "Abundance Project," a major astrophysical program, funded by the U.S. Air Force, to study the chemical abundances in stars, involving observations taken at

both Palomar and Mount Wilson observatories, employing ten postdoctoral researchers. Through Khan, Greenstein invited Wal to come to Caltech to join the effort. At that point in his career, Wal had never even seen a telescope, since he had been trained as a theorist. His knowledge of the United States was limited to what he learned from the novels of John Steinbeck; he worried about a country that seemed obsessed with anti-democratic thinking, as McCarthy-ism was at its peak in the 1950s.
There were, however, no real options for Wal in the United Kingdom at the time (1959), once his Ph.D. fellowship ran out. So off he went to California.

Postdoc in California

On arrival in California, which involved his first-ever air travel, Wal was immediately struck by the relative absence of class tension compared to England, and the apparently easy way people communicated with one another compared to what he had been used to. His transition to living in the United States was also made easier by the arrival of several other young postdocs from Britain, including Neville (Nick) Woolf, a fellow physics undergraduate in Manchester who, like Wal, ended up spending most of his career in the United States , at the University of Arizona's Steward Observatory, and Donald Lynden-Bell (NAS-I, 1990), a theorist from Cambridge who would go on to make seminal contributions to theoretical astrophysics and to direct the University of Cambridge's Institute of Astronomy.[2] Some of the experiences of the young Brits exploring the United States together are captured in a well-reviewed documentary film "Star Men." based on a reunion journey made by Sargent, Lynden-Bell, Woolf, and Roger Griffin in 2011, celebrating the 50th anniversary of their original 1961 road trip around the southwest United States.

Of course, part of Wal's new job at Caltech involved conducting observations using the premier telescopes in the world at the time, at Palomar and Mount Wilson. He was immediately captivated during his first observing trip to Mount Wilson—especially by the quiet and solitude that aligned perfectly with his mental image of what scientific research should be all about. Wal learned to observe with the help of some of his fellow postdocs, including Ray Weymann (NAS, 1984) and George Wallerstein, both of whom went on to prominence in their respective fields. He also worked with Leonard Searle after he arrived in Pasadena (1960), and began a collaboration that spanned many years. With fascination, Wal learned to identify spectral lines in stellar spectra (recorded on photographic plates) from Jesse Greenstein. Wal discovered that to excel identifying

2 Lynden-Bell was author of a Biographical Memoir about Wal for the Royal Society (2015); he passed away in 2018.

and interpreting spectra benefited from a very good memory and an ability to recognize subtle differences between spectra by eye; both came naturally to him.

Wal spent most of his three postdoctoral years at Caltech working on stellar spectroscopy, attracted in particular by stars with very unusual chemical properties that had yet to be understood, called "Peculiar A- Stars." Toward the end of his tenure, he became interested in another of what was then an obscure topic, the "Seyfert galaxies." At the time, Seyfert galaxies were known as unusual galaxies with extremely bright, point-like nuclei and very unusual optical spectra; they were so bright that very good spectra could be obtained using spectrometers at Mount Wilson that otherwise were used to observe nearby stars. This marked the beginning of Sargent's broadening interest in extragalactic astronomy, and galactic nuclei in particular (see below).

In 1960, Wal met in person, at a lunch table, the famous Fred Hoyle—whom he had idolized as a teenager listening to the BBC. Hoyle was visiting Caltech in connection with work he was doing with Caltech physicist Willy Fowler (1983 Nobel Laureate in physics, shared with S. Chandrasekhar) and Margaret and Geoffrey Burbidge (FRS, 1964, 1968).[3]

In 1962, Wal's visa was running out, and so he needed to move elsewhere. Wal claimed later that his decision was based on a statistical study of the number of women employed at observatories around the world, compiled from published observatory reports. The two leading organizations in that respect were the Royal Greenwich Observatory (RGO) in Sussex, UK, and the Dominion Astrophysical Observatory in Victoria, British Columbia; he accepted a job at the former. In fact, this strategy worked out exceedingly well: in 1963 he met Anneila Cassells, who had arrived to work at the

Anneila Cassells and Wal Sargent, 1964; they were married later that year.

3 There is a famous paper often referred to simply as "B^{2}FH," for Burbidge, Burbidge, Fowler, and Hoyle 1957 "Synthesis of the Elements in Stars" [11]– the only astrophysics paper (that I know of) with its own Wikipedia page.

RGO after completing her undergraduate degree in physics at the University of Edinburgh. They married the following year, in 1964.

Aside from the distinct upturn in his personal life, Wal did not enjoy working at the RGO, as he found it to be a rather moribund scientific environment. He had been enticed to accept the RGO position in large part because of a promise that he could spend one year of the three-year term at the Radcliffe Observatory in South Africa—but this opportunity never materialized. Wal was anxious to relocate to a more vibrant research institution as soon as possible. While attending a conference in Germany in 1963, he met Geoffrey and Margaret Burbidge (both of whom were also native Britons), who were helping to start a physics department at the new campus of the University of California (UC San Diego) in La Jolla. When the Burbidges heard about Wal's predicament, they immediately offered him a job as an assistant professor; he accepted without hesitation, as it would provide him access to the recently-commissioned 120-inch telescope on Mount Hamilton, near San Jose. Besides, there were very few opportunities in the United Kingdom for observational optical astronomers, which by this time is what Wal had become.

Back to America

As it turned out, Wal and Anneila spent only eighteen months in La Jolla, a third of which was actually spent in Australia, at the Mount Stromlo Observatory of the Australian National University, where Wal's collaborator Leonard Searle had recently moved. Anneila had enrolled as a graduate student at UC San Diego and was taking physics classes. In February 1964, Wal received an unexpected phone call from J. Beverly (Bev) Oke, one of the young faculty at Caltech, asking him if he would be interested in coming back to Caltech as a faculty member. Wal claimed later that he never understood why Caltech had chosen him over other possible candidates. Geoffrey Burbidge, his boss at UC San Diego, magnanimously advised him to take the Caltech job. Since neither he nor Anneila were particularly happy in La Jolla, it was advice he was happy to follow. So the Sargents moved to Pasadena in 1966, where Wal would spend the next 46 years as a Caltech professor.

The Hale Observatories

At the time of Wal's arrival in Pasadena, the astronomers using the 200-inch telescope on Palomar Mountain (about 120 miles southeast of Pasadena, in northern San Diego County) were divided between Caltech and the Carnegie Institution of Washington, whose Mount Wilson Observatory headquarters are located just across town from

Caltech, on Santa Barbara Street in Pasadena[4]. At that time there was a fairly rigid system in place that separated the "dark time" from the "bright time" astronomers, referring to the phase of the moon when their observations were conducted. Dark time was reserved for those observing the distant extragalactic universe, with bright time assigned to those working on stellar spectroscopy. Since up to this point the latter had been Wal's area of expertise, he was initially compartmentalized among the bright time users. But Wal's scientific interests were evolving toward the extragalactic universe, and away from working only on stars. In order to break into the dark time "club," Wal needed to identify a topic that was not already "claimed" by a more senior astronomer. Here Wal's natural attraction to mysterious outlier objects—those that did not quite fit into the prevailing picture and as a consequence had so far eluded attention—was beneficial.

Wal's initial foray into 'dark time' astronomy involved a class of objects that had been cataloged during the early 1960s by Caltech astronomer Fritz Zwicky—the so-called "Zwicky Compact Galaxies." Zwicky is widely recognized today as a pioneer who was so far ahead of his time that his prescience was only fully appreciated decades later. For example, he was the first—in 1933—to show that the relative radial velocities of galaxies moving in the gravitational potential of a galaxy cluster (the largest bound objects in the universe, with total mass of ~ 10^{15} times the mass of the Sun) implied that the total mass of the system must exceed that of the stars comprising the constituent galaxies by a factor of several hundred. This could only be explained by the presence of vast amounts of invisible "dark matter" (a term he coined). This was some 40 years before dark matter was widely accepted in the community. In any case, Zwicky was a hero to Wal—probably due to a combination of his brilliant ideas, "outsider" status, and curmudgeonly-yet-generous personality.[5]

The Zwicky compact galaxies were objects that did not appear to conform to either spiral or elliptical morphology as in the classical Hubble "tuning fork" diagram, but instead were very compact and significantly "bluer" in color than typical galaxies. Wal explained that many of the dark time astronomers at the time did not believe that compact galaxies even existed, and therefore he would not be infringing on anyone's scientific territory by observing them. Wal undertook a survey to obtain spectra of a substantial subset[29]; discoveries resulting from the survey formed the basis for much of Wal's work through

4 The combination of the telescopes on Mount Wilson and Palomar Mountain were jointly run by the two institutions, collectively known as the "Hale Observatories," between 1948 and 1980.

5 Along with photographs of Anneila and his daughters Lindsay and Alison, the file cabinet behind Wal's desk in Robinson Hall also featured two photos of Zwicky; one of them is famous in astronomy circles, showing a bolo-tie-wearing Zwicky gesticulating in a way that seems to indicate a profound disappointment in his colleagues.

the late 1960's and early 1970s, working with colleague Leonard Searle, who had moved back to the Carnegie Observatories from Mount Stromlo Observatory in 1968.

Young Galaxies and the Primordial Helium Abundance

As recently as the late 1960s, the abundance of helium in the universe was not well understood, in spite of the fact that it is the second-most common element after hydrogen. The problem was that the nuclear reactions capable of synthesizing He^4 in significant quantities required very high temperatures and densities—higher than could be produced in the cores of normal stars. It was known that the mass fraction of helium in the sun is 0.25, but there remained speculation about whether stars with much lower than solar heavy element abundances would also have significantly lower He abundances. For several years, Sargent and Searle had been searching for Galactic stars with low heavy element abundances (such as those in globular clusters) in order to measure the helium abundance in stars that should have closer to primordial composition. It turned out to be impractical to measure accurate He/H ratios in the stars that were bright enough to enable detailed spectroscopic study, so that a different approach would be needed.

At a Vatican Observatory conference, 1970. Wal is rightmost in the photo; Fred Hoyle is to Wal's right, with Martin Rees (FRS 1979) immediately behind Hoyle.

It turned out that, among the Zwicky Compact Galaxies, a subset had spectra strongly resembling those of individual HII regions (regions of ionized gas excited by very hot young stars, commonly found in the parts of spiral galaxies harboring new star formation). Because of the very intense H and He-ionizing radiation field of the most massive (youngest) stars, strong emission lines due to recombination of H and He could be measured together with emission from atomic levels of atoms and ions of heavy elements excited by collisions with free electrons in the same gas. By measuring the relative intensities of the various emission lines, and modeling the stars responsible, Searle and Sargent showed that one could simultaneously measure the abundance ratios He/H, O/H, and Ne/H in the gas phase.[6]

In a famous paper [37] Sargent and Searle highlighted the method by applying it to two of the Zwicky compact galaxies, whose spectra appeared to be completely dominated by newly-forming stars, with no evidence for significant past star formation, despite their discovery in the nearby universe. These young galaxies, at most a few hundred million years old, apparently had somehow either not yet formed or remained in a quiescent state over many billions of years before "turning on" in the relatively recent past. The most extreme among these were physically very small—less massive than typical galaxies like the Milky Way by a factor of 1000. They constituted a "local" laboratory where one might hope to observe directly the appearance and physical properties of primeval galaxies. For typical galaxies like the Milky Way, observing the same phase would have been possible only in the first few billion years of cosmic history, which would not be routinely accessible to telescopes for another 25 years. Searle and Sargent showed that the abundance of heavy elements like oxygen and neon, which are produced only in stars and then dispersed into the interstellar gas by supernova explosions—were under-abundant (relative to hydrogen) by a factor of ~ 4–20 compared to the ratio observed in the Sun and in the ionized gas of typical nearby spiral galaxies. This strongly suggested that the interstellar gas in these compact "dwarf" galaxies was closer to "primordial" in composition than had ever been observed in a galaxy with young stellar populations. They also showed that one implication of their discovery is that such young, "metal-poor" galaxies must contain more gas (by mass) than stars—whereas a typical spiral galaxy like the Milky Way has stars outweighing gas by at least a factor of 10.

Searle and Sargent then showed that, unlike the low abundances of heavy elements relative to H, the He abundance was nearly identical to that in the Sun; they concluded therefore that the measured value of He/H must be primordial. Their measurement of primordial He/H was timely: the value was similar to that predicted by calculations of "Big Bang Nucleosynthesis" (e.g., [20, 43])–where He^4 formed as a natural consequence of nuclear reactions that were expected to "freeze out" at the density and temperature in the universe that would have prevailed two or three minutes after the Big Bang itself.[7]

6 Similar methods are still used to measure gas-phase abundances in rapidly-star-forming galaxies over most of cosmic history.

7 The "Hot Big Bang" theory itself had first been proposed in the 1940s, but most of the modern development of the theory, and the first direct observational results, occurred during the 1960s. It was still not universally accepted even by the early 1970s – Sir Fred Hoyle was famously one of its detractors, espousing instead the so-called "Steady-State" theory – but it had recently found strong theoretical and observational support, especially after the 1965 detection of the cosmic microwave background [21], one of its strongest predictions.

The primordial abundance of He^4 constituted additional observational confirmation of the Hot Big Bang, and the method of using metal-poor dwarf galaxies, pioneered by Searle and Sargent, remained the most reliable one for decades to follow.

Left to right, Fred Hoyle, Donald Clayton, Geoff Burbidge (with cricket bat), Willy Fowler, and Wal Sargent (with baseball glove), 1970.

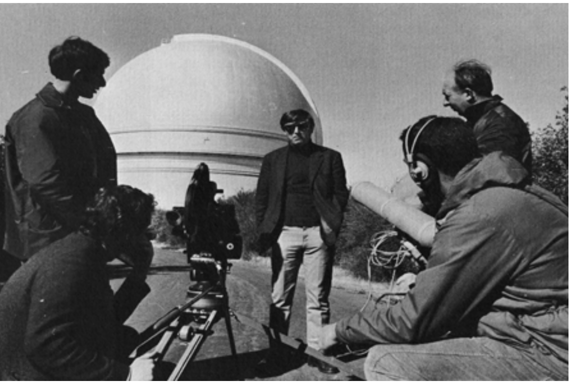
Sargent, Searle, and collaborators then developed more general methods for connecting the observed spectra of galaxies to their star formation histories over time ([38]); variations of the methods they developed remain major tools for galaxy evolution research today.

Active Galaxies and Supermassive Black Holes

By the mid 1960s, the phenomenology of quasars was an extremely fast-developing field. The earliest examples were first identified with sources of radio waves detected by radio astronomers in the 1950s in the first surveys of the radio sky. The radio sources were subsequently shown to be "star-like" on photographs taken with optical telescopes.[8]

The first definitive spectroscopic identification was made in 1963 by Wal's Caltech colleague Maarten Schmidt (NAS-F 1978)—showing a high redshift of $z = 0.128$ for 3C 273 ("3C" refers to the Third Cambridge catalog of radio sources). Quasars had theorists scratching their heads to explain how so much energy could be produced within such a small physical region; meanwhile, additional quasars, including ones with redshifts that placed them more than 10 billion light years distant (if indeed their redshifts were cosmological—which at the time remained debatable). Edwin Salpeter (NAS, 1967)[26] had postulated that the implied luminosity of quasars could be produced by accretion of material onto a massive black hole—an idea that was not widely accepted at the time, since black holes themselves were still believed by many to be mere theoretical constructs. It is hard to appreciate that something we consider "incontrovertible truth" today—that "supermassive" black holes develop at the centers of essentially every galaxy, and that their growth process over cosmic time produces roughly the same amount of energy as all of the stars that ever shone in their host galaxy—was fiercely debated through the 1960s and 1970s.

8 The name "quasar" is an acronym for "quasi-stellar radio source."



Wal during the filming of the BBC television program "The Violent Universe" (1969), in front of the Palomar 200-inch Hale telescope. In the finished program, Wal explains the phenomenon of Seyfert galaxies.

The reader will recall that Wal had developed an interest in a class of spiral galaxies with point-like nuclei and odd-looking spectra, the Seyfert galaxies, during his first stay at Caltech in the early 1960s. On his return to Caltech, he worked with colleague Bev Oke on a spectroscopic study of the brightest example known of this class, called NGC 4151 [19], in which they noted some of the similarities the nuclear spectra bore to quasars; however, the luminosity was much smaller, and there was no doubt as to its location at the center of a bright spiral galaxy. Even more puzzling was the absence of strong emission at radio frequencies, which had so far been a key signature of quasars.

In the course of mining the Zwicky compact sources, Wal discovered that a few of them seemed to be extreme versions of Seyfert galaxies like NGC4151—but in this case their nuclei were so bright that they completely dominated the luminosity of the system, and because of their more extreme distance compared to the nearby Seyferts, the host galaxy was difficult to see at all (hence their appearance in a catalog selected according to their visual compactness). These bright Seyfert galaxies had many of the same characteristics as quasars—broad emission lines of the hydrogen Balmer series and ground-state resonance lines of heavier elements, the absence of stellar photospheric absorption features (showing that even the continuum light was non-stellar), and very "blue" energy distributions. However, the distant Seyferts were also "quiet" at radio frequencies compared to the quasars. Nevertheless, Wal speculated that these luminous objects were in fact the "missing link" between Seyfert galaxies and quasars [27, 28]. He was correct.

Advances in Instrumentation

As of the early 1970s, despite the existence of large-aperture optical telescopes (by this time, in addition to the Palomar 200-inch and Lick 120-inch telescopes, new 4m telescopes were being commissioned in Arizona [Kitt Peak National Observatory] and Australia [Anglo-Australian Observatory]), spectroscopy of faint objects remained extremely challenging. By far the limiting factor was the detector technology—photographic plates—which suffered from very low efficiency (only about 1 percent of incident photons would be detected on a typical emulsion) and non-linearity, i.e., the signal recorded is not linearly proportional to the incident signal. Obtaining a spectrum of a faint object, even one of relatively low spectral resolution, remained a heroic undertaking even with the largest telescope. There was a potentially vast amount of physical information waiting to be extracted from the spectra of galaxies and quasars, but most of it remained beyond reach for all but the brightest examples.

Wal Sargent with French astronomer Jean Audouze (1973).

In the spring of 1973, physicist Alec Boksenberg (FRS 1978) of University College London was visiting Caltech, and he introduced himself to Wal in the hallway of the Robinson building, which housed the optical and radio astronomers at Caltech at the time. He told Wal about a new detector system he had invented, capable of recording the signal from extremely faint sources photon by photon, without associated detector noise, with ~ 20 times higher detective quantum efficiency than photographic plates, and with linear response: the Image Photon Counting System (IPCS). By the end of the same year, Sargent and Boksenberg used the IPCS on the Palomar 200-inch Coudé spectrometer for their first observing run in what would prove to be a long and extremely fruitful collaboration. The IPCS, when attached to spectrometers on large telescopes, qualitatively changed the sensitivity of faint-object astrophysical spectroscopy and, in the process, opened up entirely new areas for study.

Masses of Galaxies and Black Holes from Stellar Dynamics

During this time in the mid-1970s, Sargent had become increasingly interested in using spectroscopy of stellar systems—i.e., elliptical galaxies, dwarf galaxy satellites of the Milky Way, Milky Way globular clusters—as a quantitative means of measuring total mass. The basic idea is that the stellar systems, e.g. the stars within an elliptical galaxy, or the satellites of the Galaxy, are bound by gravity and moving at speeds that depend on the distribution of total mass internal to their orbits. In the case of the Galactic satellite systems, the mean radial velocity of each could be measured from the redshift of the stellar absorption lines in the integrated light of its stars; for elliptical galaxies—the most massive stellar systems known—the total masses are large enough that the relative velocities of the stars (as a function of projected position in the galaxy) could be measured from a spectrum by determining the degree to which the stellar absorption lines are broadened relative to those of a single star—called the "velocity dispersion." To turn an ensemble of radial velocity or velocity dispersion measurements into estimates of total mass as a function of projected radius of a system then required making a dynamical model constrained by the data. Wal capitalized on the new spectroscopic capabilities to conduct some of the seminal work in observational galactic dynamics ([14, 31]).

In the spring of 1976, Sargent and Boksenberg, together with Caltech graduate student Peter Young, Kitt Peak astronomer Roger Lynds, and members of the instrument team from UCL installed Boksenberg's[10] IPCS on the Kitt Peak 4m telescope. They focused their observations on the nearest giant elliptical galaxy, Messier 87 (M87), the central galaxy in the Virgo Cluster, the nearest large cluster of galaxies. Since M87 is relatively nearby, it is well-resolved by ground-based telescopes with typical angular resolution of 1 arc second, so that the spatial dependence of the stellar velocity dispersion could be measured on relatively small physical scales, enabled by the high quality digital spectra coming off the IPCS. Their spectacular result was published in 1978 ([34]): they showed that the velocity dispersion (σv) of the stars in M87 increased by almost a factor of 2 within the inner 1 second of arc of the galaxy's light profile, which proved that there was a large amount of mass within a small physical region. They concluded that the increase in σv in the center could be explained by a highly-concentrated mass of $\sim 5 \times 10^9$ times the mass of the Sun, almost certainly a super-massive black hole. In fact, twenty years later, similar observations using the Hubble Space Telescope in [13, 17]) confirmed this interpretation using higher spatial resolution, and in 2019, the Event Horizon Telescope made the definitive measurement of material just about to disappear into the black hole. The mass inferred for the M87 black hole: 6.5 × 109 solar masses; Sargent et al had measured it correctly to within 20%, based on observations conducted 35 years earlier.[9]

The method employed by Sargent, Young, Boksenberg et al. to measure the black hole mass is the same technique used in later years, with higher spatial resolution allowing for measurement of lower-mass black holes, by the Hubble Space Telescope. The demographics of supermassive black holes at the centers of nearly all relatively massive galaxies

9 In fact, the 1978 measurement was closer to the EHT mass measurement than those based on Hubble observations in the mid-late 1990s.

Wal at his desk in Robinson Hall, 1974.

has engaged a substantial fraction of the astrophysical community since that time.

Wal's interests in supermassive black holes and their connection to AGN activity continued through the 1980s. With then-graduate-student Matthew Malkan, Wal revisited the energy distributions of active galaxies and quasars ([18]), taking advantage of the wider range of wavelengths over which spectra could be measured, using infrared and ultraviolet observations in space. They showed that, in addition to the power-law non-thermal (non-stellar) continuum that had been identified previously, there was excess energy in the blue and UV part of the spectrum that could be well fit by models of thermal emission from an accretion disk surrounding a black hole—this was a strong prediction of theories of black hole growth. A few years later [12] Wal and former student Alexei Filippenko (UC Berkeley, NAS 2009), who had recently finished his Ph.D. working with Wal on low-luminosity active galactic nuclei, began a large spectroscopic survey of the 500 nearest galaxies. The goal, among many others, was to search for evidence of lower mass black holes in apparently normal galaxies, "A Search for Dwarf Seyfert Nuclei." This was one of the most ambitious single projects ever undertaken using the Palomar 200-inch telescope, and marked the first of Wal's projects at Palomar to use CCD detectors (rather than the IPCS), for sensitive spectroscopic observations.[10]

The observations were conducted over 50 clear nights between 1984–1990, but the publications resulting from it were still being produced in the late 2000s. A quick perusal finds ~ 30 papers published, with 5000 citations, between 1985 and 2009;

10 CCDs, or charge-coupled devices, had been improving rapidly since the first were tested on the Palomar 200-inch telescope in the late 1970s, led by James Gunn (then at Caltech; NAS 1977) and James Westphal. They are now used in essentially all instruments operating on the ground over the wavelength range 0.3-1 microns, and can achieve more than 90% detective quantum efficiency with very low detector noise.

it includes the Ph.D. work of several astronomers who went on to become the next generation leaders of their field (e.g., Luis Ho, Aaron Barth, and Jenny Greene).

The Intergalactic Medium

By 1967, the growing number of quasars with reasonably high-quality spectra had revealed that, in addition to the smooth non-stellar continuum and broad emission lines, there were also numerous narrow absorption lines recorded in the spectra. These lines required higher spectral resolution for detection compared to the prominent broad emission lines used to measure the quasar redshifts. Over the next few years, some of the strongest lines were identified with ground-state transitions of astrophysically abundant metallic ions, and Wal had collaborated with then-Caltech-colleague John Bahcall (NAS, 1976) on some of the early work [2, 1]. Most puzzling—and therefore, potentially very interesting—was that many of the identified absorption lines were found at redshifts different from that of the quasar itself, sometimes by a very large amount, usually lower. At the time, the community was divided about whether to believe that large quasar redshifts were cosmological in origin, i.e. that their redshift was due to the expansion of the universe first noted by Edwin Hubble in the late 1920s. A non-negligible fraction of astronomers found it more plausible that the red shifts were caused by either extreme masses or extreme velocity material (moving at a substantial fraction of the speed of light) ejected by relatively nearby galaxies. Doubters of cosmological quasar redshifts found it more likely that the narrow absorption lines at lower redshifts were caused by material ejected at lower velocity (and thus, with lower redshift as seen by an observer on earth) from the same source. The alternative interpretation was that the lower-redshift absorption line systems were produced when the light path between the quasar and the observer intercepted intervening pockets of gas along the way, and their lower redshifts indicated smaller distances from the observer. The two alternatives became known as the "ejection hypothesis" and the "intervening hypothesis."

In 1970, Kitt Peak National Observatory astronomer Roger Lynds (NAS, 1974) had obtained the spectrum of the quasar 4C05.34, with a redshift of $z = 2.877$, the highest redshift known at the time by a substantial margin—high enough to observe all the way to below rest-wavelengths of 1000 Å in the quasar rest frame. Lynds noted the very high density of narrow, unidentified absorption lines whose positions were confined to wavelengths shortward of the quasar's Lyman α emission line at 1216 Å; he speculated that the most likely explanation for these lines was to identify them as Lyman α absorption at lower redshift than that of the quasar, with each line representing neutral H at a discrete redshift [16]. The fact that there were no corroborating features at the same redshifts from metallic species (as had been true of the previously identified redshift systems) was puzzling, but Lynds suggested that observations with higher spectral resolution of a number of high-redshift quasars could help to understand their physical origin.

Although Wal had "dabbled" in working on the narrow quasar absorption lines during the early days of the subject in the late 1960s [2, 1], he was frustrated by the difficulty of obtaining spectra with adequate quality for making progress. He found the subject itself—identifying and understanding the implications of a fundamentally new astrophysical puzzle—extremely appealing, in the same way that peculiar A stars and Seyfert galaxies had done earlier in his career. The first observing run for his new collaboration with Boksenberg and his "Flying Circus" (as the team from UCL was called who made the IPCS work on each observing run, with reference to the "Monty Python" television program that had just finished its run on the BBC) was in October, 1973 on the Palomar 200-inch telescope. Over the next 15 years, Sargent, Boksenberg, and, from 1976, the brilliant Peter Young[11] published a series of papers [9, 33, 35, 44, 45] that would revolutionize the subject of quasar absorption lines, using IPCS data taken at Palomar and at the new 4-meter telescope at the Anglo-Australian Observatory, where they commissioned a clone of the IPCS in 1976.

Wal and his collaborators turned the subject of quasar absorption lines, which had been a curiosity related somehow to the quasar phenomenon, into a new field involving detailed study of gas in intergalactic space between galaxies (the "intergalactic medium," or IGM) through most of cosmic history. As the team acquired spectra of a significant number of high-redshift quasars at high spectral resolution, they developed new statistical techniques and analyses that showed clearly that most (but not all) of the absorption lines were produced by cosmologically intervening gas, along the line of sight and therefore at redshifts lower than that of the quasar. The quasar, while interesting in its own right, in this case acted as a conveniently bright beacon whose relatively smooth and featureless intrinsic spectrum made it ideal for recording the presence of even minute quantities of intervening gas. Perhaps the best-known single paper Wal ever wrote, and the one about which he was most proud, appeared in 1980 [35]. This paper showed that the "Lyman-α forest" of absorption lines shortward of the quasar Lα emission line, was caused by diffuse hydrogen gas in the IGM which, they argued, were highly ionized due to the

11 Young, who had been the top mathematics student in Cambridge as an undergraduate, finished his PhD at Caltech in 18 months, with Wal as his advisor, on the dynamical effects of supermassive black holes in galaxy nuclei. He was appointed to the Caltech faculty after spending one year as a postdoc. His career in astrophysics spanned only 5 years, from 1976-81, during which he was first or second author on 36 papers, 12 of them with Wal. Tragically, he took his own life in September 1981, at the age of 27.

intense metagalactic radiation field, possibly produced by rare but luminous quasars. They used sophisticated statistical methods, many of which were new to astrophysics, to show that the “Lyman-α clouds” were much more widely distributed in space than galaxies, and that the relatively rare absorption systems that also contained lines of heavy elements were distinct also in their kinematics, which resembled those expected from metal-enriched gas in galaxy halos. Thus one could separate the intervening absorbers into those likely to be intergalactic—and possibly of primordial composition—and those that arise when the line of sight intercepts gas that has been enriched by galactic star formation. The paper itself was so long and comprehensive that it had to be published in *The Astrophysical Journal Supplement* series rather than the main journal. It could have been several separate papers, given its content.

Subsequent papers established the statistics of the heavy element systems, which required a larger number of independent quasar lines of sight due to their much lower rate of incidence, which established the first evidence for cosmological evolution of the intergalactic medium, and further evidence connecting heavy element absorption systems with intervening galaxies at redshifts $z > 1.5$. Throughout the 1980s and early 1990s, Wal and collaborators worked hard to compile samples that could be used to understand the evolution of the galaxies themselves [30, 32, 42], since at the time quasar absorption line techniques provided essentially the only direct observational constraints on galaxies beyond redshifts $z \sim 0.5$.[12] The surveys in the late 1980s to early 1990s, all conducted using the Palomar 200-inch telescope, were ambitious enough to remain relevant some fifteen to twenty years after publication.

The Keck Observatory

In the meantime, in 1984 Caltech and the University of California had agreed to collaborate to build a next-generation optical/IR telescope that would constitute the largest increment in telescope aperture since the Palomar 200-inch telescope superseded the Mount Wilson 100-inch telescope in 1948: the W. M. Keck 10m telescope, to be sited on Maunakea, a 14,000-foot dormant volcano on the “Big Island” of Hawaii. The Keck telescope used a new-segmented mirror technology that had been developed by Jerry Nelson (NAS, 1996) and his colleagues at Lawrence Berkeley Labs.[13]

12 I remember my first conference, entitled “High Redshift and Primeval Galaxies”, which Wal sent me to in 1987; I was to talk about the clustering of heavy element absorption systems at redshift $z= 2.5$, while the deep galaxy surveys were just reaching $z=0.4$.

13 A very similar technology is also being used for the James Webb Space Telescope, the European Extremely Large and the Thirty Meter Telescope projects.

During the years 1984–1993, Wal spent a huge fraction of his time on the development of the Keck Observatory as a co-chair of the Keck Science Steering Committee, a group of scientists that oversaw nearly every aspect of the project that touched on science, from scientific requirements to the design of the support facilities. It is impossible to overstate the importance of this group, and Wal's co-leadership of it, during the nearly ten- year period between project inception and first light—it played a large role in making the Keck Observatory a scientific success out of the starting gate.

One of the first-light instruments for the Keck telescope,[14] and the first to be commissioned along with the telescope in 1993, was the High Resolution Echelle Spectrometer (HIRES), built at UC Santa Cruz by a team led by Steven Vogt. HIRES achieved "first light" along with the telescope in 1993, and it arguably represented the second quantum leap for the study of the intergalactic medium. Prior to the arrival of Keck+HIRES, there had been only a handful of observations of high redshift quasars at sufficiently high spectral resolution to resolve the intrinsic widths of the intervening absorption line systems (resolving power of $R = \lambda/\Delta\lambda \sim 50000$, to be compared with $R \sim 5000$ used for most of the previous "high resolution" work), essential for quantitative analysis of the physical properties of the gas. The gain was not attributable to the increase in telescope aperture alone (which accounted for a factor of ~ 4): in addition, the Maunakea site delivered image quality a factor of ~ 2 (or more) sharper than the best nights at Palomar, meaning there was a background contribution ~ 4 times smaller that would need to be subtracted from the quasar signal. HIRES itself was state-of-the-art, of course, with 2–3 times higher efficiency than previous high resolution spectrometers, and the spectra were recorded on a low-noise CCD detector. The net 10-20 fold gain in the rate of detected photons increased the number of quasars bright enough to observe at high resolution from a handful to hundreds. Moreover, all of a sudden it was possible to observe bright quasars for many hours and achieve S/N per spectral resolution element measured in the hundreds.

Wal was quick to capitalize on Keck/HIRES, and it remained his principal research tool from 1993 until the end of his career in 2012. The quantum leap in the information content of the absorption line spectra was matched by comparable progress in the theoretical understanding of the IGM observed by the Lyα forest: cosmological hydrodynamic simulations were indicating that, rather than diffuse intergalactic "clouds" confined by the pressure of a hotter, less dense medium (as [35] had postulated), the

14 A second Keck telescope was commissioned 5 years later, in 1998, made possible by the further generosity of the Keck Foundation and the addition of NASA to the partnership.

Lyman-α forest was caused by slightly denser regions of a diffuse IGM that traces the filamentary dark matter structure on large scales. The forest was still produced by low-density gas with temperatures of ~ 10^4 K, photo ionized by the metagalactic UV background, but they need not be in equilibrium, but can expand with the universe and respond to changes in the intensity of the ionizing field with cosmic time. It also turns out that, once the correct interpretation of the data is understood, most of all baryonic material in the high redshift ($z > 2$) universe was outside of galaxies, in regions within a factor of ~ 10 of the mean density averaged over all cosmic volume. The Lyman-α forest had become a tool enabling a relatively model-independent measure of the matter fluctuations in the universe. It had become interesting to cosmologists because it was tracing small fluctuations that have not been altered beyond recognition by gravitational collapse from their initial conditions.

Although Wal provided his HIRES data to many theoretical astrophysicists interested in cosmological applications, he was not particularly interested in measuring anything cosmological himself (and certainly not parameters like Ω_m or H_0; he was more interested in using physics to interpret the observations toward understanding "what is out there." He focused his own team's work in a few areas that reprised his long-term interests: measuring the chemical composition and cosmic evolution in gas associated with both the diffuse IGM and in higher-density absorbers believed to be associated with forming galaxies [15, 36, 39, 40, 41]; the small-scale structure of absorbers, using HIRES spectra of multiple-image quasar gravitational lenses [22, 23, 24, 25, 5]; and the IGM at redshifts approaching the reionization era [3, 8, 4, 6, 7].

Wal also maintained his long-standing collaboration with friend and colleague Alec Boksenberg throughout the "HIRES era;" together they wrote what would be Wal's final paper [10], many years in the making, and, in the tradition they had established together twenty-five years earlier for especially weighty contributions to the subject [35], nearly 100 pages in *The Astrophysical Journal Supplement* series. A moving quotation from the acknowledgments section, written by Alec Boksenberg: "Foremost, I want to acknowledge Wallace Sargent who passed away in 2012 October. He has been my best friend from the time we first worked together at Palomar exactly 41 years ago. A true gentleman, he excelled not only in science but also widely in many cultures. He inspired and helped me in countless ways and I am forever grateful to him. Also, we had great fun together. He is the founding worker of all in this paper."

AWARDS AND HONORS

Wal became a Fellow of the Royal Society (United Kingdom) in 1981, an honor he recalled being unable to enjoy due to the untimely death the same year of Peter Young, his former Ph.D. student and recently appointed faculty colleague. Wal steadfastly maintained his "resident alien" status for forty years after returning to California in 1964. One reason (I speculate) was that he quite enjoyed his status as an "outsider." He would often profess to be a socialist politically (he was a 3rd generation Labour Party voter on his father's side, and his grandfather was active as an organizer for the local Labour Party), which was rarely taken seriously by those who knew him, though Wal was at least partly serious about it. I learned recently from a transcription of an interview that he and his friend and collaborator Leonard Searle had jokingly established their own expatriate political party called the "Elitist Socialists," whose basic tenet was that competence should be rewarded, regardless of the origin or background of those who demonstrate it. Wal believed that this was close to being realized by U.S. academia (his own case being a good example) but that it had been less true in Britain, at least historically. In any case, in 2004 Wal finally decided to become a naturalized U.S. citizen after holding out with only a Green Card for forty years; he was elected to the NAS the following year.

Wal received many other honors over the course of his career, including a fellowship from the Alfred P. Sloan Foundation (1968), the Warner Prize of the American Astronomical Society (AAS) in 1969, the Dannie Heineman Prize of the AAS and American Institute of Physics (1991), the Bruce Gold Medal of the Astronomical Society of the Pacific (1994), and the Henry Norris Russell Lectureship (2002), the highest honor bestowed by the AAS.

"EXTRACURRICULAR" ACTIVITIES

Wal always claimed that he was never asked to serve on committees within Caltech, because it was known by the "powers that be" that he would do a terrible job. Wal had a natural tendency to view authority with suspicion, and his relationships with administration tended toward the adversarial. He was not a politician, and would not hesitate to say the wrong thing at the wrong time, especially if it would stir things up a bit. It was sometimes hard to tell

AAS President Anneila Sargent, presenting Wal with the AAS Russell Prize Lectureship (January 2002).

how much of this was meant seriously and how much was in service of maintaining his "independent outsider" persona. Whatever the reason, his outbursts were often very funny! Remember that Wal idolized Fritz Zwicky.

In spite of his resistance to authority and sometimes impolitic behavior, in reality Wal shouldered more than his fair share of responsibility within the department and in the general astrophysics community. He served as Executive Officer for Astronomy (i.e., department chair) for two separate terms, 1975– 81 and 1996– 97, and as Palomar Observatory Director from 1997– 2000. He was Vice President of the AAS from 2004–2007 (an elected position), and served on the AAS Committee for the Status of Women in Astronomy 1998– 2001. His advice was highly valued and often sought by universities and scientific organizations throughout the world; Wal served on some thirty visiting committees over his career, and was a visiting fellow, often in connection with a prize lecture, at many institutions in North America, the United Kingdom, and Europe.

As a teacher, Wal would admit confidentially that he was never entirely comfortable; however, if he was nervous it was never noticed by the students. His class lectures would typically combine relatively formal blackboard derivations with a liberal sprinkling of hilarious editorial comments about the usefulness (or not, as the case may be) of the subject being discussed. I think he enjoyed seeing the looks of surprise on the faces of students in reaction to his more "colorful" humorous asides. At one time or another I think Wal taught every course (undergraduate and graduate-level) offered in astrophysics, and was a firm believer that it was "good for us and good for the students" to have faculty tackle new classes every few years. He never took a sabbatical leave, and he taught classes every year from 1964– 2012.

Wal was justifiably proud of the cohort of graduate students he supervised over the course of his career—a total of 18, according to his personal web page devoted to the subject. He introduced his "Graduate Student" page with the following: "All of my Ph.D. students are listed below. Remarkably, like me, they almost all showed a reluctance to work for a living and instead found jobs in academia." His track record with graduate students was exceptional—nearly all went on to distinguished academic careers (as of 2019, three have been elected to the NAS), specializing in a range of scientific areas that reflects the breadth of his own contributions to astrophysics over his career.

PERSONAL RECOLLECTIONS

I admit that I am one of those 18; I was Wal's only graduate student and the only member of his research group at Caltech during the years 1984– 89 (Alex Filippenko had just finished his Ph.D. and was leaving to take up a Miller Fellowship in Berkeley as I was arriving). I remember my first meeting with Wal (thirty-seven years ago this October) in his office in Robinson Hall, during the first few weeks of the academic year. Although I never told Wal, I had come to Caltech expressly to work with him after hearing his colloquium at my undergraduate institution the previous spring. I was terrified in anticipation of the meeting, and not entirely sure I had a right to approach him to ask for a project, since I had been warned by more senior graduate students that one had to be "chosen" to work with Wal. As it happened, he quickly put me at ease, and gave me something to work on: my first project was to reduce quasar spectra that he and Alec Boksenberg had collected using the IPCS at Palomar over the previous few years. It was the first time I had ever worked with real astronomical data.

Over time I learned to relax in Wal's presence; in reality I had nothing to fear, as one-on-one Wal turned out to be funny, irreverent, and keenly interested in many subjects both within—but especially outside of—astronomy. I have very fond memories of the many nights we spent observing together at Palomar, which provided opportunities for rambling conversations and the telling of stories. Wal was an aficionado of classical music, about which I was totally ignorant, while I had worked in college radio as an undergraduate and so was well-versed in obscure alternative/indie rock, blues, reggae, etc. I was surprised how curious Wal was to learn more about what I knew. We also bonded over baseball, which Wal had studied as an intellectual pursuit before he ever set foot in the United States, and had been a Dodgers fan since their move to Los Angeles from Brooklyn. I was also happy to discover that Wal enjoyed reading as much as I did, so we traded opinions and recommendations. There were certain routines that one followed during observing runs with Wal: perhaps most important was the ceremonial stroll around the catwalk.[15]

The ostensible reason for it was to check the weather, to see if clouds were approaching from any direction. But its real purpose was to look at the sky. About halfway around (always proceeding clockwise), after our eyes were fully dark- adapted, we would stop. Looking out at the night sky, Wal would say in a reverential tone "Ah yes…can you believe that they pay us to do this?"

15 A narrow walkway attached to the exterior of the dome, about 50 feet off the ground, that extended over the full circumference.

Anneila, Lindsay, Alison, and Wal Sargent (1975).

Wal very rarely called me by my actual name; instead, he would refer to me as "Team," which was (I think) meant ironically, since it was only me he was talking to. I was also called "his nibs," which I understood to be a Britishism with mildly derisive connotations, but I was too sheepish to ask and was pretty sure that it was meant to be humorous in any case. Wal would visit me in my office at least daily, to find out how things were going, and exchange gossip, which he enjoyed immensely. He also liked to pretend to be ignorant of all American popular culture (part of maintaining his "outsider" persona) and ask me or my office mates naive questions about it, as if we were his only direct link to all things American, despite his decades spent in southern California. From Wal, I learned about sumo wrestling, Manchester United, oriental carpets, and the Goon Show—just a few of his many interests.

Wal had an uncanny ability to inject humor into any situation in danger of becoming overly serious, quite necessary for calming a neurotic young graduate student such as myself. I still have a mental archive of many of the things he said that still cause me to laugh out loud on recollection; unfortunately, almost none of them can be repeated in polite company. Wal had amusing nicknames (most of which also cannot be repeated here) for many faculty and staff in the department, and (especially) anyone in administration. In spite of his willingness to shake things up a bit, Wal was actually quite shy, as he would readily admit. This shyness could come across as formality to someone who did not know him well, but really it was unease. Once you got to know him, you would see how far from the mark this first impression was.

I feel incredibly fortunate to have worked with Wal—almost from the beginning he treated me like a colleague, and I like to think that we also became friends while I was still a student. We worked very closely, and in some cases we wrote papers literally together, meaning we sat in the same room at the same time and composed sentences out loud together, after which I would type it in to the computer (Wal's typing never advanced beyond hunt-and-peck, which was painful to watch). We shared some personality traits and non-scientific interests that strengthened the bond. Both of us had spouses who were much more outgoing and social than we were ourselves. We spent many a departmental party or pre-colloquium tea "skulking" (Wal's word) together off to the side somewhere, which came quite naturally to us both. A certain degree of self-deprecation also resonated—Wal referred to his daily mid-morning coffee with friend and colleague Maarten Schmidt, on a bench outside Robinson Hall, as a meeting of the "Dead Wood Society."

Looking back on my formative years as a Caltech graduate student, it is hard to recall ever receiving direct advice from Wal, and yet somehow he profoundly influenced the way I view science. In my personal view, the principal characteristics that Wal passed on to his students are a taste for interesting problems, healthy degrees of skepticism and humor and an attitude that celebrates unexpected turns and tangents that frequently arise when one "looks to see what is out there."

I also feel lucky to have had Wal as a colleague for seventeen years, from 1995– 2012. Although we had not worked together directly since completing some collaborative work in 1992, I could look forward to almost daily visits from Wal, where he still called me "Team" and, as always, the topic of conversation would be wide-ranging. Wal liked to wander the halls and pop in to check on people—something very few people would take the time to do nowadays. Wal especially enjoyed visiting with the graduate students, who always appreciated the interest he showed in their general well-being.

I miss Wal for much more than his scientific accomplishments—he was a close friend.

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