Allan Sandage was an observational astronomer who was happiest at a telescope. On Hubble’s sudden death Allan Sandage inherited the programmes using the world’s largest optical telescope at Palomar to determine the distances and number counts of galaxies. Over many years he greatly revised the distance scale and, on re-working Hubble’s analysis, discovered the error that had led Hubble to doubt the interpretation of the galaxies’ redshifts as an expansion of the universe. Sandage showed that there was a consistent age of Creation for the stars, the elements and the Cosmos. Through work with Baade and Schwarzschild he discovered the key to the interpretation of the colour–magnitude diagrams of star clusters in terms of stellar evolution. With others he founded Galactic Archaeology, interpreting the motions and elemental abundances of the oldest stars in terms of a model for the Galaxy’s formation. He published several fine atlases and catalogues of galaxies and a definitive history of the Mount Wilson Observatory.

ANCESTRY AND EDUCATION

Allan Rex Sandage was proud to come from a mid-west farmer’s family which had moved from South Carolina to Indiana and, in 1881, to Lone Rock, Harrison County, Missouri; he was born in Iowa City in 1926. Allan was the only child of Charles H. Sandage, soon to become a professor of business at Miami University in Oxford, Ohio, and Dorothy Maud Sandage née Briggs, daughter of George Nathaniel Briggs, president of Graceland College, Iowa (a Reformed Mormon foundation, now Graceland University). Charles Sandage’s father, Moses Sandage, was a farmer in Lone Rock and had two other sons and a daughter, but Charles was the only one who went to high school. He proceeded to Graceland College and on to the State University of Iowa, where he worked his way through graduate school to obtain a PhD in business administration.

Oxford was a small town in southern Ohio, and Allan grew up under austere conditions during the Depression; orange juice was the height of luxury! His was a university-oriented family with a father and mother who strongly supported his will to learn. They were not practicing Mormons, and on occasion he attended the local Methodist Church. His father had struggled to get his education, so Allan always expected a hard road with four years of undergraduate work followed by four years to get himself a PhD in science. However, this was looked upon as a tremendous opportunity, a very enjoyable part of life. His interest in science was sparked when the family moved temporarily to Philadelphia where his father worked...
for the government in 1936–37. One of his boyhood friends there had a telescope, and—on looking through it in the backyard—Allan was caught by the wonder of astronomy. Back in Ohio he read all he could find on mathematics and science. His schoolteachers realised his interest and helped him both by after-class tuition and by suggesting further books. “The Glass Giant of Palomar” by David O. Woodbury was published in 1940 when Allan was 14. This book contained a history of the Mount Wilson Observatory, and he realised that it was possible to make astronomy one’s profession. But at that stage he had no inkling that he would become the most prominent user of the great Palomar reflector, whose construction was delayed by World War II. Eddington’s books and Hubble’s “The Realm of the Nebulae” were other sources of inspiration. In summer 1941 his father had a teaching appointment at Berkeley. On the way there they took the opportunity of visiting both the optical shop at Santa Barbara Street and the observatory itself on Mount Wilson.

His father’s war-work was in Boston, so his parents moved to Cambridge, Massachusetts. But Allan, then 16, remained in Ohio with student accommodation at Miami University, where he majored in physics. Professor Ray Edwards headed a physics department of only three, but he instilled in his students the importance of precision, dedication, excellence and honesty that remained hallmarks of Allan’s work throughout his life.

In 1944 he volunteered for the Navy and went into the electronics maintenance programme for 18 months, first in Chicago, then at Gulfport, Mississippi. There he met many other scientists, including the astronomers Arthur Code and Albert G. Wilson, who was later responsible for the first Palomar sky survey with the 48 inch Schmidt. After a three-month training course, they were moved to Treasure Island in San Francisco for a further nine months.

At the end of the war his parents moved to Urbana, Illinois, where his father was appointed professor of advertising. Living at home with the government benefits from the G.I. Bill made it possible for Allan to resume his studies in the much larger physics department of the University of Illinois. In later years Allan had little contact with his father, who became very prominent in advertising, but he remained very close to his mother. He became a heavy smoker, but when she died of cancer in 1970 he smoked his last cigarette. Jeans’s book “Physics and Philosophy” gave him a strong interest in the philosophy of science, and this led him to further reading in philosophy. At Illinois Professor Robert Becker, who had been at Caltech, taught analytical mechanics; at first Allan found the problems too hard, but with Becker’s help he mastered them. There were no quantum mechanics or relativity courses, but he got an excellent grounding in electromagnetism, optics and mathematical physics. He majored in physics and mathematics with a minor in philosophy, but meanwhile he started a junior research problem in astronomy under Prof. Robert H. Baker. The techniques he learned there were very valuable for his later work at Caltech. The project itself was part of a larger one co-ordinated by Prof. Bart J. Bok of Harvard, who visited the observatory and invited Allan to his observing summer school at the Agassiz station of Harvard. There he met Vaini Bappu, who later did much for Indian astronomy, and Halton (‘Chip’) Arp who will reappear.

In 1948 Allan applied to be a graduate student in physics at Caltech, but in his letter of support Prof. Loomis, head of physics at Illinois, mentioned his strong interest in Astronomy. Lee DuBridge, replying to Allan’s application, said the graduate School in astronomy was just beginning and “you have been accepted in that school at Caltech”. Although Fritz
Zwicky was in Physics, Jesse Greenstein was the sole professor of astronomy for those first years; there were four graduate students and he taught all the courses: stellar atmospheres, stellar interiors, the interstellar medium, practical astronomy and astronomical methods of observation. Allan was much in awe of such erudition.

Astronomy students were required to take physics courses. Helmut Abt, a fellow student who remained a staunch friend for life, recalls that he and Allan puzzled hard over Prof. King’s optics problems, at first separately and then together, but got nowhere. Later in class Mr. Ferrell was called upon and immediately gave an elegant solution to the first problem, then Mr. Parker likewise solved the second in two lines. Sandage and Abt felt outclassed. It later transpired that Ferrell was the only Caltech student with straight ‘A’s all through, and Eugene Parker became a world expert on magnetohydrodynamics at Chicago. Sandage claimed it was Abt’s levelheadedness that helped him survive the courses. Both had a hard work ethic that pulled them through.

Among the other students in their first year was Morton Roberts, who became a radio astronomer and, following Babcock’s early work, produced good evidence for dark matter in the outer parts of the Andromeda Galaxy. It was this that drew Vera Rubin into that subject. Among those in the following year was Chip Arp. Harden McConnell, later a professor of chemistry at Caltech and then Stanford, writes of that time: “We lived in what was then called the greasy spoon, a somewhat tumbled-down frame building on campus that housed graduate students. I bunked in the same room as Donald Glaser, of bubble chamber fame; next door were Roy Craig, a chemistry student, and Allan. Graduate students of my vintage tended to be rather sober. The PhD qualifying exams were demanding and designed to flunk a fraction of the class; research could be equally demanding. Allan struck me as quite distinct from the other students. I don’t think I ever saw him without a smile and something pleasant to say. I never did learn the source of his inner happiness, but it was certainly there.”

THE KEY TO STELLAR EVOLUTION

Walter Baade was on the staff of Mt. Wilson. During World War II the darker sky due to the blackout in Los Angeles had enabled him to resolve the central parts of the Andromeda nebula and show that the brightest stars there were red, like the brightest stars of the globular clusters. This led to his concept of Population II.

Sandage and Arp asked Baade for a pre-thesis research project. He suggested locating the main sequence in the globular clusters. Although their brightest stars were far from the main sequence, it was assumed nevertheless that much fainter stars would probably lie on it. Baade taught the two graduate students how to use the 60 inch telescope on Mount Wilson, and they took plates of the globular cluster M92. Meanwhile, Baum provided a faint photoelectric sequence in the cluster. Arp and Sandage shared the hard work of plate measurement, and within a year they had a preliminary result. Then Baade got Palomar 200 inch plates that went deeper and that gave them a definite identification of the main sequence and a rough estimate of its slope.

About that time Hubble asked Greenstein if there were a capable graduate student who could help with his programme on galaxy counts. Following a suggestion of Eddington’s, his aim was a better determination of $N(m)$, the number of galaxies per unit area of sky
of magnitude $m$, in order to discover the geometry of space. Hubble took plates on the 48 inch Schmidt dithered so that each star gave a square of uniform blackening on the plate. By measuring the blackenings on different plates, a photoelectric sequence of stars of known brightness could be transferred from one area to another. Hubble wished to have reliable sequences down to the 18th magnitude. After getting Sandage started, Hubble departed for the summer of 1950. Sandage found inconsistencies of three tenths of a magnitude in the transfers and took on another short project under Greenstein while he awaited Hubble’s return.

Hubble did not return as expected. He had suffered a serious heart attack while fishing and needed time to recuperate. When he came back he wished to continue accumulating plates of the M81 group of galaxies to identify Cepheid variables. However, his health was too poor to endure the long nights in the observing cage of the 200 inch telescope. So, after some initial instruction from Humason, the job of taking these plates fell to Sandage, who later described his reaction: “Oh, it was fabulous. I can’t really reconstruct the first three or four months of that period, so much was happening. First of all, it was an opportunity that was beyond any imagination, observing with the 200 inch, and secondly, working on the long-range programmes of cosmology with Hubble. And at the same time being a graduate student, trying to pass the courses in physics and astronomy—so it was a very high-pressure atmosphere. The work on the mountain was an escape, but you knew that your sins would catch up with you, because you were four days away from campus and courses, and you were pretty well swamped. I’d bring the plates back and have a consultation with Hubble. He would then decide what to do next.” Meanwhile, with Baade as his adviser, he had decided that his thesis topic would be the determination of the colour–magnitude diagram of the globular cluster M3. With the work on M92 well on its way, he already knew the methods, and M3 offered the prospect of seeing more of the main sequence.

Martin Schwarzschild (ForMemRS) was a great friend of Baade’s and visited Mount Wilson every year. The new results on M92 and the preliminary results on M3 were very exciting to Schwarzschild, who had been working theoretically on the evolution of the core of a star after it has burned all its hydrogen. He invited Sandage to come to Princeton and work on the interpretation of his results for a year, once his observations were complete. Meanwhile, Sandage’s work had so impressed Baade and Hubble that, even before he completed his PhD, Bowen, the director, offered him a staff position at Mount Wilson and Palomar Observatories. This was a dream come true, and in 1952 Allan set out for his post-doc at Princeton, still without a PhD, but with his dream-job assured on his return. The eight months in Princeton turned his work on M92 and M3 into a seminal discovery. For the first time, the evolutionary tracks across the colour–magnitude diagram fitted real data. Sandage and Schwarzschild understood that the turn-off point from the main sequence gave a method by which stellar ages could be determined. With their 1952 paper it became clear that at last theories of stellar evolution had real power to explain the facts. (In 1963 Sandage and Schwarzschild were jointly awarded the Royal Astronomical Society’s Eddington medal for this work.)

At the end of his time at Princeton, Sandage joined Baade, who took part in the summer school organised by Leo Goldberg in Ann Arbor Michigan. Later Sandage wrote a lively account of his return to California. “I had been Baade’s student during the previous four years, and we had come to feel somewhat at ease with each other. Baade had decided to
buy a new car at the factory in Detroit, to take delivery on the last day of the school, and to then drive the long road back to California, asking me to ride with him. Ed Dennison drove us both to the factory pickup place for a new 1953 Chevy. After the car was in Baade’s possession, Ed said he would follow us for a few miles simply to see if all was OK. We started down the road out of Detroit toward California. Baade (essentially a new driver) was driving half on the road and half on the shoulder (sometimes), or half on his side of the road and half on the other oncoming side, alternatively. Ed signalled us to stop and enquired through the rolled-down window if there was something wrong with the steering wheel. Baade, sensitive, said all was OK, thank you very much, and we would be on our way. A few minutes later we unfortunately were! Baade had no sense of micro-compensation in steering; he would keep the wheel in a rigid position until it was clear he had to change, not microscopically, but grossly, long after it had become evident that it was required to do so. We went across the country for six days in large triangles, first going toward the middle of the highway and then towards the corn or wheat fields, or later towards the canyon drop-offs on the right. The first day was by far the worst because I was frightened. I offered to drive, but like all great men Baade believed in himself and thought only he could save us from the oncoming drivers, who were astounded when we got close enough to see their faces, and who Baade believed were simply poor drivers that should be denied access to the road. The trip became a bit easier as it wore on because I could not help but sleep for most of the day, avoiding the constant thrill of the road. To save expenses, we had agreed to share a double room in the motels along the way each night. However, Baade was a most accomplished snorer, so accomplished that it is simply impossible to describe. . . . After two nights of no sleep for me, but restful sleep for the driver, I slept away many of the driving hours. But the real memory of that trip was the conversation about astronomy on that cross-country adventure. Baade, like all scientists of substance, had a set view of how things were put together, to be sure a view to be always challenged by the scientist himself, but defended as well against all less informed mortals who objected without simon-pure reasons. The trip then became a riding commentary on much of the world of astronomy and astronomers. But that is a rather different story than the magic of the summer of 1953, which in many ways began the outside world’s discussion of Baade’s ideas that, together with Schwarzschild’s, spearheaded the modern understanding of stellar evolution.”

Not long after Sandage returned to take up his new post at Mount Wilson and Palomar Observatories, Hubble died of a second heart attack. Just as the mantle of Elijah fell on Elisha, bringing with it the awesome responsibility for Israel, so Hubble’s cloak fell on Sandage, carrying with it responsibility for furthering Hubble’s cosmological programmes. No other telescope could carry out such work, on which rested the reputation of the world’s greatest observatory. Sandage knew he was a good astronomer; now it was his duty to prove himself to be a great one. With Schwarzschild he had already broken open the field of stellar evolution. Later, such understanding of the stars could be used to further cosmology, but for the next decade his major research was devoted to understanding stars.

At the Vatican Conference on Stellar Populations, organised by Father O’Connell, Sandage was the star performer, giving no less than four talks explaining the way that stars evolved and how their ages could be found from the colour–magnitude diagrams of their clusters. Also in 1957, Sandage gave lectures at Harvard on the observational approach to stellar evolution. In the audience was Mary Connelley, then a graduate student at Radcliffe, hav-
Figure 1: Walter Baade with Tom Matthews (fishing) at Bass Lake during the Michigan summer school organised by Leo Goldberg in 1953. Photograph by Owen Gingerich.
ing taken her first degree at Indiana University in Bloomington. She had replaced Alice Farnsworth as head of astronomy at Mt. Holyoke for three years, but she first met Allan much earlier in 1950, and again a year or two later at a conference in Michigan. In 1959 Allan Sandage and Mary were married. He often claimed that Mary had saved his life. When he came home from the office exhausted, disappointed, furious or desperate, Mary would be kind, gentle and patient. His temper would soon cool.

His close friends were Helmut Abt, Geoffrey Burbidge, Olin Eggen and Chip Arp. Later, when Arp espoused the concept of large non-cosmological redshifts on flimsy evidence, that friendship broke for a decade. Allan felt responsible for getting Chip onto the Observatory staff, and to be so unscientific was for him ‘sinning’. Yet he never broke with Geoffrey Burbidge who also espoused non-cosmological redshifts.

In 1958 Sandage visited South Africa with his friend Olin Eggen to work on the Magellanic Clouds. In Pretoria they were guests of the Thackerays. Mary Thackeray had a strict rule against talking shop, which Sandage found quite a strain, but—though nervous—he enjoyed playing Father Christmas to the children. At the invitation of the Astronomer Royal, Sir Richard Woolley FRS, he also visited the Royal Observatory at Herstmonceux Castle in Sussex, where later Eggen became chief assistant.

THE COLLAPSE OF THE GALAXY

In stars of normal metal abundance like the Sun, the atomic absorption lines crowd together at the ultraviolet end of the optical spectrum, blanketing out some of the light. Metal deficient stars are relieved of this blanket, so have an ultra-violet excess in comparison to normal stars of the same colour.

Around 1959 Sandage and Eggen realised that this was a quick way of classifying stars by their metal abundances. Following a lead found by Nancy Roman, Eggen had been studying motions of nearby stars across the sky and had produced a catalogue of stars with large transverse motions. He and Sandage measured these stars photoelectrically and took spectra to get radial velocities of those that lacked them. Most stars in the solar neighbourhood move in nearly circular orbits around the Galaxy and have metal abundances not very different from the Sun, however the stars in Eggen’s catalogue dived through the plane of the Milky Way and had orbits that took them both much further in and further out from the galactic centre. Some even went backward around the Galaxy. They were all metal deficient, and their colour–magnitude diagram showed that they were, like globular cluster stars, among the oldest in the Galaxy.

One of us (DL-B) was a post-doc working with Sandage at that time, and we discussed what these findings meant. Since the stars were among the oldest, the rest of the Galaxy must have been gaseous then. The gas could not be so hot that it was supported against the Galaxy’s gravity by pressure, as it would then be far too hot to make stars. Thus the gas clouds must have been cool and followed the diving orbits still seen in the stars. But that is unsustainable; unlike the stars, the gas clouds would collide. In the 1962 paper widely known as ELS, we concluded that the Galaxy formed in a dynamical collapse during which the metal-deficient stars were formed. But this collapse ended in starburst activity in which the gas clouds collided, the rate of star formation rose to balance the influx of gas and the metal abundance rose to values not far below solar.
ELS became the most cited single paper of each of its authors. It laid the foundations of what has come to be called galactic archaeology, which now uses much more detailed abundances of the different elements and correlates these with stellar motions. More recent work on galaxy formation puts emphasis on galaxies merging; small galaxies have too little gravity to hold in supernova debris, so cannot hang on to their metals. Such systems are still merging with the Galaxy, adding their metal deficient stars to our halo. The concept that the Galaxy initially formed in dynamic collapse is nevertheless correct, because the emission from a hot gas at galactic densities cools more rapidly than the free-fall time.

QUASARS AND QUASI-STEellar OBJECTS

One of the burning questions of the early 1960s was the nature of radio sources found by Ryle’s group at Cambridge and by the Australians. Greenstein had convinced Caltech president Lee DuBridge of the importance of radio astronomy, so money had been allocated to create the Owens Valley Radio Observatory (OVRO), and John Bolton, a Yorkshireman, had been brought over from Australia to get it going. The Cambridge group had made the observations for the third Cambridge catalogue. The $2 \times 5$ arc-minute positions were given to Henry Palmer of Jodrell Bank, who had developed the radio-linked interferometer whose aerials were spread across England and Wales. This he used to determine the angular diameters of the radio sources. Tom Matthews of OVRO attended a conference at which Palmer gave his results, including about 30 sources with parts of such high surface brightness that they were unresolved. Thinking that these small sources might be the most distant and therefore the most interesting, Matthews asked Palmer for a list of those sources. He returned to Caltech with this list, and Bolton readily agreed to a programme in which R. B. Read refined the Cambridge positions at Owens Valley by using a wider north-south separation of the dishes. It was hoped that these sources could then be identified optically. Sandage took 200 inch plates centred on the refined positions. The possible identifications which appeared to be galaxies were then given to Maarten Schmidt of Caltech, who had taken over Minkowski’s program on distant radio galaxies.

However, among the first identifications was 3C 48 in which a 16th magnitude star lay in the error box. Was this the first radio star? In October 1960 Sandage photometered the star and found it to be abnormally bright in the ultraviolet. He then took its spectrum. It was quite unlike anything he had seen before, just a number of emission lines superposed on a continuous spectrum. The wavelengths of the emission lines made no sense. They did not correspond to those of any known element. Sandage took his spectrum to Bowen, who had made his name by identifying the nebular lines at 3726, 3729Å with forbidden lines of oxygen. Bowen could not interpret the spectrum, but said that Greenstein had been studying the spectrum of highly ionised oxygen. He was consulted too, but still the spectrum made no sense.

In the autumn of 1961 the Burbidges visited, and we all saw the direct plate of 3C 48. Attached to the starlike image was an extremely faint wisp, which could only be seen if the plate was viewed at a glancing angle. We all knew of the problem posed by the spectrum. Quite soon afterwards Sandage returned from observing and excitedly announced that 3C 48 must be a star. It had varied by 0.3 magnitudes over a few months, far too rapidly for a galaxy of several thousand light-years in diameter. This larger variation convinced him that
the small night to night variations he had seen in January 1961 were definitely real. Other mysterious radio sources soon followed. 3C 286 and 3C 147 had fewer emission lines, but also had ultraviolet excesses. Eventually a lunar occultation observed in Australia gave a very accurate position for 3C 273, and the position coincided with a 13th magnitude star. Schmidt took the spectrum, which had numerous unfamiliar emission lines. On being pressured to publish by the radio astronomers, Schmidt finally saw that, if he ignored the brightest lines, the others were spaced not unlike the Balmer series. The Balmer series they were indeed, but with a redshift of 0.158. Never before had such a bright object been found with such a large redshift. Greenstein then understood the spectrum of 3C 48 and published its redshift with Matthews. To Greenstein the discovery was a vindication of his founding of Owens Valley and an emergence of his Caltech astronomy department from being overshadowed by the expertise of Mount Wilson, but Sandage, who regarded 3C 48 as his object, was omitted from the party. He had been left uninvited by the very professor whom he so admired as his teacher. However, he continued to study further quasars, and the next major discovery was his.

What Sandage discovered was that the quasars were not isolated rarities, but the radio-loud members of a much larger set of objects (QSO) which had relatively little radio emission. We know of no other paper that was received by the Journal on the day of its publication, but Subramanian Chandrasekhar (FRS), who was editor of the Astrophysical Journal, had a high opinion of Sandage and held up publication so that his paper announcing the quasi-stellar galaxies could be included. This paper was written in the excitement of discovery. Sandage failed to allow for a significant contamination of the number counts at the brighter magnitudes by white dwarfs. This caused controversy until their contribution was sorted out via spectroscopy. However, Sandage’s basic point was correct; QSOs far outnumber quasars. In 1969 his result was used by DL-B to estimate the number of dead QSOs. He concluded that they were probably giant Black Holes and roughly as numerous as large galaxies. On hearing his theory that galactic nuclei were collapsed old quasars, Sandage wrote to get him an extra invitation to the 1970 Vatican conference on the Nuclei of Galaxies.

More recent work shows QSOs to be strong in X-rays and even in gamma rays, and it is now accepted that they are powered by material that is heated as it spirals down into black holes of many million solar masses. In this sense, Sandage was the discoverer of the large number of giant Black Holes in the Universe.

THE AGE OF CREATION

When Sandage and Schwarzschild first realised that main-sequence turn-off points allowed them to find the ages of star clusters, the age of the Earth was thought to be about three billion years. They hoped to get a similar figure for the old clusters. Baade’s work on M31 had shown it to be at about twice Hubble’s original distance estimate, but Hubble’s estimates of other distances and redshifts gave a timescale of only 1.8 billion years. Soon after his return from Princeton, Sandage inspected the best 200 inch plates. He found that many of the objects in other galaxies that Hubble had thought were their brightest stars, were now resolved into tight knots of several bright stars embedded in ionised hydrogen regions. Hubble, by assuming that these were single stars similar to the brightest stars of the Milky Way, had attributed to them too low a luminosity and had therefore got his
distances too small. Thus Hubble's discrepancy between the time at which the galaxies were close together and the age of the Earth was now removed, and the age of the old star clusters seemed to agree also. Sandage was delighted by this consistency of three different methods of age dating, which was in tune with his strong belief that science is a consistent body of knowledge.

However none of the methods was secure. The estimated age of the Earth is now 4.6 billion years. Hubble's pioneering estimates of galaxy distances could be improved with photometric magnitudes of faint stars and by finding cepheids in other galaxies, and the age of the globular clusters from stellar evolution depended on the poorly-known masses of the stars at the turnoff point. Furthermore, both the helium and the metal abundances in those stars affect the age determination from stellar evolution theory. Perhaps it is not too surprising that these ages have over the years ranged up to 18 billion years, although no modern estimate is less than 10 billion. Sandage derived 11.5 billion years for his beloved M3 and two other globular clusters. In Figure 2 we have plotted different estimates of the inverse of the Hubble constant, which is a time, against the date at which the estimates were published.

Most stars are too dim to be seen in other galaxies. Thus only the very rare, extremely bright stars can be used as “standard candles”. The problems of measuring distances to
them are: Firstly, can we recognise precisely the same type of stars, and how accurately do these stars have the same luminosity? Secondly, can we find similar stars in our galaxy and measure the distances accurately through the murk of dust in which we find ourselves? Cepheid variables are very valuable, as their periods can be measured accurately. Cepheids of a given period have a quite well-defined luminosity. The dimmer short-period Cepheids are common enough that the distances to some in our galaxy can be measured directly. The Pole Star is one such, but it is only the brighter ones that are useful to measure the large distances needed for determining Hubble’s constant. There are a few bright Cepheids in the Milky Way whose distances can be measured with the desired accuracy. For many years these problems were circumvented by using the Large Magellanic Cloud (LMC), our nearest satellite galaxy, as an intermediary. It has both the bright long-period Cepheids and the dimmer short-period ones, so these can be calibrated against one another. Since the 1980s, with the advent of CCDs, it has been possible to measure LMC stars as faint as the main sequence. However in the Galaxy and in other large galaxies the stars have greater metal-abundances than in the LMC, and the luminosities of Cepheids of a given period depend on the metal abundance. Sandage and his main collaborator, Gustav Tammann of Basel, wrestled with such problems for 45 years. Gradually, instrumental improvements, the coming of CCDs rather than photographic plates, and the high resolution of the Hubble Space Telescope (HST), which allowed more Cepheids to be identified and measured, eased the problems.

The measurement of Hubble’s constant had been singled out as a key project for the HST, but the project was shared over a large team which Sandage and Tammann did not join. The team effort eventually found a Hubble constant of $72 \pm 3$ (random) $\pm 7$ (systematic) km/s/Mpc. In their last paper, Sandage and Tammann did not agree, finding $62.3 \pm 1.3$ (random) $\pm 5.0$ (systematic) km/s/Mpc. Time will tell which estimate is closer to the truth. The work has been highly productive also in isolating good secondary distance indicators, which could be used to great distances. First Sandage, often supported by Jerome (‘Jerry’) Kristian, found that the brightest members of clusters of galaxies were quite good standard candles, but the real gem came when Sandage and Tammann worked to turn supernovae into standard candles, an idea that Sandage attributed to Zwicky.

**TYPE Ia SUPERNOVAE**

A 1968 paper by Kowal, who worked with Zwicky and Wallace Sargent (FRS) to discover supernovae, found that supernovae of type I reached the same luminosity at maximum to within 0.61 magnitudes.

Sandage and Tammann realised this could be further refined by restricting consideration to supernovae of type Ia. Such a bright standard candle could eliminate many of the intermediate steps in the determination of the distance scale. In 1991 Sandage therefore wrote an observing proposal for the Hubble Space Telescope to calibrate via Cepheids the distances to those nearby galaxies in which supernovae of type Ia have been observed. The brightest classical novae decline from maximum light faster than the dimmer ones, but for supernovae Mark Phillips discovered that the dimmer ones decline faster. This correlation allowed the luminosity at maximum of a type Ia to be predicted to within 0.2 magnitudes, and this spread can be even further reduced by using the colour. To carry out the detailed
work of Cepheid discovery and measurement Sandage and Tammann asked others to join
them, and Abi Saha was delighted to join. He was the lead author on the HST Cepheid
work, which lasted fifteen years and found many Cepheids in each of the dozen galaxies
studied. In their final paper summarising the results of this campaign, Sandage, Tammann
and Saha—using the best local Cepheid calibration available—derived a Hubble constant of
$62.3 \pm 5.2 \text{ km/s/Mpc}$. They point out that the difference between this value and that of the
Key project is primarily due to their use of this different local calibration.

THE SOUTHERN OBSERVATORY

In 1964 Horace Babcock and Sandage went to Bowen, the director, and proposed that the
future of the observatory lay in expansion into the Southern hemisphere. This had been a
dream of Hale’s from the early days. Bowen felt there was too much to be done to ensure the
success of the Palomar 200 inch by improving its instrumentation and that of the Mt. Wilson
telescopes. Any Southern Observatory would divert effort from that. However, Babcock and
Sandage pressed their point, and eventually Bowen agreed to fund site-testing in the South.
This was organised by Babcock. It soon became apparent that the European Southern
Observatory’s choice of Chile was a very good one, but the site-testing still took five years.
Eventually the Carnegie team chose Las Campanas, a site somewhat higher and more remote
than ESO’s La Silla. Babcock and Sandage made the case for a southern 200 inch telescope
in collaboration with AURA (the Association of Universities for Research in Astronomy).
This got very close to being funded by a large grant from the Ford Foundation together
with the NSF, but, just as it was being agreed upon, a new head of the Ford Foundation
was appointed who had other views. Eventually both large grants went to AURA without
Carnegie involvement.

Sandage flew back from his sabbatical in Australia and joined Babcock to meet Crawford
Greenewalt, a trustee of the Carnegie Institution and chairman of its astronomy subcommittee.
Greenewalt, being a scientist and engineer, understood the importance of the Chile
site. From this meeting came a strong commitment by Greenewalt to support the Carnegie
Southern Observatory (CARSO), if a suitable site was found. Although many of his staff
thought Chile was rather remote and were not in favour of diverting funds there, Babcock
was rightly convinced that this was the frontier where the observatory’s future lay. In late
1968 he met President Eduardo Frei and, to his surprise, obtained instant permission to
purchase nearly 100 square miles of land including Cerro Las Campanas. The Carnegie In-
stitution purchased the tract within months. Henrietta Swope had already given the bulk
of her inheritance anonymously to develop the site and put a 40 inch telescope there, which
was inaugurated in 1971 and bears her name. In lieu of an unaffordable 200 inch, Babcock
and engineer Bruce Rule advocated a lesser telescope, and a generous gift by Crawford and
Margaretta Greenewalt made possible the completion in 1976 of the 100 inch Irénée du Pont
telescope, named in honor of Mrs. Greenewalt’s father. Thus by the time Babcock left as
director, the du Pont was established on one of the world’s best sites. He, Bowen, and Arthur
Vaughan had insisted on very good optics to match the excellence of the seeing. When it was
first commissioned, there were no spectrographs yet, but a remarkably wide field covering
2.2 square degrees at the Cassegrain focus. With many of the staff less than enthusiastic
about going all the way to Chile and many awaiting the spectrographs, Sandage felt he must
show what the telescope could do in its present form. He first completed his programme for the Revised Shapley Ames catalogue and then devised the Virgo cluster survey, described below.

Sandage greatly admired Babcock’s foresight and tenacity in getting Las Campanas built. However this was achieved when funds were scarce, and the Caltech astronomers felt that Palomar needed more instruments, those on Mount Wilson were old and there was too much light pollution from Los Angeles. Unsurprisingly, they had the feeling that they were sharing their magnificent 200 inch telescope with the Carnegie astronomers and were not getting much back. There was also friction over appointments. Because the telescopes were operated in common, both staffs had a say in staff appointments and they sometimes disagreed. By the time Maarten Schmidt succeeded Babcock as director in 1977, tensions between the Carnegie and Caltech staffs made the joint observatory meetings contentious. Schmidt decided that the problems would be best resolved by dissolution of the union that had run the observatories jointly for 30 years. Sandage opposed the breakup, which he considered unnecessary, but afterwards he broke off relations with Caltech. It is interesting to speculate that—had the union lasted a few years longer, so that more Caltech staff experienced the wonderful conditions in Chile—then perhaps the differences could have been resolved with freedom to appoint staff, but no formal split.

The growth of Las Campanas meant that Carnegie funds remained scarce, and despite the Mt. Wilson site having better seeing than Palomar, the brighter sky led to less pressure to update the equipment there. Finally, to Sandage’s horror, Mount Wilson—the home site at which the history of 20th-century astronomy was concentrated—was abandoned by the Carnegie Observatories. Sandage, with his collaborator Gary Fouts, used it to the last, securing a much better database than that available to ELS. They confirmed a significant thick-disc population of stars with between one tenth and one third the metal abundance of the Sun, which had been advocated by Gilmore and Reid. Sandage’s very strong feeling for the history of astronomy meant that he was particularly hurt by the decision to abandon Mount Wilson.

**GALAXY CLASSIFICATION AND SURVEYS**

Upon Hubble’s death in 1953, Sandage inherited his unique collection of photographic plates of nearby galaxies obtained with the large Mt. Wilson reflectors. With it fell upon his shoulders the task of carrying out Hubble’s intended revision of his initial galaxy classification system of 1926. This initial classification—based on earlier efforts by Max Wolf in Heidelberg and Heber Curtis at Lick Observatory—had proposed three main classes of extragalactic ‘nebulae’: amorphous ellipticals, spirals and irregulars, and had found its culmination in the famous ‘tuning-fork diagram’ published in “The Realm of the Nebulae” (1936). Guided by notes and fragments of a manuscript written by Hubble, plus memories of discussions with him, Sandage undertook the revision. He supplemented the Mt. Wilson plate collection with many new plates obtained at the Hale 200 inch and Schmidt 48 inch telescopes on Palomar. After extensive visual inspection of plates old and new, he described the revised morphological classification system in “The Hubble Atlas of Galaxies”, published in 1961 by the Carnegie Institution of Washington and lavishly illustrated with photographs of 176 individual galaxies. His detailed description of the revised Hubble types included crucial new
evidence for the existence of Hubble’s S0 galaxies, a hypothesized transition type between the amorphous, red and dead elliptical galaxies and the bluish disk galaxies with their splendid spiral patterns. The Hubble Atlas remains one of Sandage’s most cited publications to date; coming at the right moment after the dissemination of the Palomar Observatory Sky Survey prints, it made large-scale photographs of galaxies obtained with the world’s largest telescopes available to all astronomers, enabling them to type galaxies seen on the prints by comparison with the prototypes of the revised Hubble classification.

In 1975, Sandage supplemented his classification with an extensive review of various galaxy classification schemes developed by astronomers throughout the 20th century. Though rarely cited, his review chapter in Volume IX of *Stars and Stellar Systems* is still well worth reading. The landmark volume itself, entitled “Galaxies and the Universe”, was co-edited by Allan with Mary Sandage and Jerry Kristian. Sandage was well aware of the great potential value of uniformly conducted surveys. He admired the Harvard all-sky survey of 1246 bright galaxies, down to 13th photographic magnitude, published by Shapley and Ames in 1932, and decided early on to collect and measure redshifts for all these galaxies and to reclassify them on the revised Hubble system. A crucial part of this effort was the imaging of all Shapley-Ames galaxies south of declination −15 degrees, the general limit of Hubble’s Mt. Wilson galaxy plate collection. Beginning in 1974 with the Swope 40 inch telescope at Las Campanas, and continuing with the du Pont 100 inch telescope after its 1977 commissioning, Sandage photographed as many of the southern galaxies as possible, classified them, and in 1981 published—with Gustav Tammann—the “Revised Shapley-Ames Catalog of Bright Galaxies”, often referred to as RSA. Besides a complete listing of all Shapley-Ames galaxies giving their revised Hubble types and measured redshifts, the RSA contained high-quality photographs of 84 type-defining galaxies arranged in 15 panels. A novel feature of the catalog was that it included intrinsic-luminosity classes, on a system first proposed by van den Bergh, for most spiral galaxies. In 1987 Sandage and Tammann published a second edition of the RSA with improved types for about 200 galaxies, based on new Las Campanas plates. If the two editions of the RSA are combined, they replace ELS as Sandage’s most cited publication. To accompany and supplement the RSA, Sandage and Bedke published in 1994 “The Carnegie Atlas of Galaxies”, two massive volumes showing high-quality photographs of 1168 Shapley-Ames galaxies obtained with the large reflectors at Mt. Wilson, Palomar, and Las Campanas. In his preface, Sandage commented: “Given the evident responsibility to preserve this unique photographic record, we deemed that the way to make the collection available for widest possible use was to compile this atlas.”

A surveyor of galaxies at heart, Sandage also exploited the exceptionally wide field of view (1.5 × 1.5 degrees) and excellent plate-scale (10.8 arcsec/mm) of the du Pont telescope to conduct a survey of the Virgo cluster of galaxies from Las Campanas. The survey consisted of 67 large (20 × 20 inch), blue-sensitive photographic plates covering an area of about 140 square degrees centered on the famous nearby cluster. It yielded a catalog of 2096 galaxies, of which 88% were judged to be likely or possible cluster members. In six papers published 1984–87 Sandage and his collaborators (mostly Tammann and Bruno Binggeli) described the properties of Virgo cluster galaxies, introduced a new classification system for the dwarf members, and determined the structure and kinematics of the cluster itself. A key conclusion, congruent with developing knowledge of galaxy clusters, was that the cluster core and envelope are both still forming, whence the Virgo cluster is young.
Hubble to his dying day was very reticent about the expansion interpretation of the redshifts of galaxies. He always claimed that the numbers of galaxies at a given magnitude would not show a uniform universe if he adopted the expansion interpretation. It was Sandage’s reworking of Hubble’s data after his death that resolved this difficulty. Hubble had omitted a factor of \((1 + z)\) in correcting his magnitudes, and it was this that led to his contradiction. The removal of that contradiction did not of itself demonstrate the reality of the velocity interpretation of the redshift. One test is readily demonstrated. The redshift is independent of wavelength. Tolman devised another direct test, and Sandage undertook this test first with Jean-Marc Perelmuter and then with Lori Lubin. Surface brightnesses should appear reduced by the factor \((1 + z)^{-4}\) when they are observed at redshift \(z\). Lubin and Sandage carried out this test and, assuming the form \((1 + z)^{-a}\), they found \(a = 4 \pm 0.4\) in good agreement with Tolman’s prediction. This result was only obtained after a somewhat uncertain allowance had been made for the gradual dimming of elliptical galaxies as they evolve, but even without that correction the “tired-light” theory, which predicts \(a = 1\), does not fit.

After Hubble’s death, Sandage joined Humason and Mayall from Lick Observatory in a great paper that described the state of Cosmology in 1956. Sandage wrote the theoretical part of this paper. By then over 800 extragalactic redshifts were known as a result of long hours at the telescope. Forty years earlier Vesto Slipher at the Lowell Observatory at Flagstaff obtained some 30 redshifts, typically exposing for three nights for each one!

In his early papers on cosmology, and in particular his 1961 paper “On the Ability of the 200 inch Telescope to Discriminate Between Selected World Models”, Sandage laid emphasis on the attempt to find the curvature of the redshift–magnitude relation as a way of measuring the expected deceleration of the expansion due to gravity. Several times he reported marginal detections of such curvature in the expected direction, but all of these proved ephemeral. Later he realised that the density of the universe can be measured more easily from deviations from the smooth Hubble flow due to the significant gravity of large-scale concentrations of galaxies, such as the Virgo cluster. Sandage had always expected the density of matter to be close to the density at which its gravity causes the Universe to close. He was constantly surprised by the smoothness of the Hubble flow, so that even large concentrations of matter produced considerably smaller changes in the velocity field than he expected. Somewhat reluctantly he concluded that there was too little matter to close the Universe. Here he was quite correct. However, his intuition that the Universe should be on the edge of closure was also correct. It is dark energy, not matter, that produces most of the closure density.

When at last there were sufficient supernovae of type Ia with redshifts of about a half, other groups did find the curvature in the redshift–magnitude relation, but in the opposite sense, corresponding to a universe whose expansion is accelerating. This surprising result was soon agreed on by the two groups studying high-\(z\) supernovae, but it was also strongly backed by results from the Boomerang balloon experiment around Antarctica. These showed the first peak in the spectrum of fluctuations over the sky of the Cosmic Microwave Background, which clearly gave a value close to the closure density.
From his early reading of “The Glass Giant of Palomar” Sandage had found inspiration from the history of Hale’s Observatory on Mount Wilson. He met and knew well some of the first generation astronomers, Hubble and Humason in particular, and shared stories with others at the monastery. Many of the second generation were still on the staff when he joined in 1953. He had a deep feeling for the magic mountain, where he had started his communing with the stars, where Michelson had measured the velocity of light and, with Pease, had developed his stellar interferometer. This was the place where Hale’s laws on the magnetism of sunspots were discovered and Babcock at last measured the Sun’s magnetic field and explained its cycle, where St John had looked for Einstein’s gravitational redshift in the solar spectrum and where Adams had found it in the spectrum of the white dwarf Sirius B.

When the Carnegie Institution decided to publish a history of its work during its first century, Sandage was clearly the person to ask to write the volume on the history of the observatory. He responded with enthusiasm and produced a magnificent scholarly work, in which the whole development of 20th-century astronomy is intertwined with the history of the observatory which led the subject. Only he had the detailed knowledge of the staff and their work. He had heard their anecdotes while eating midnight lunches on the mountain. In this work he shows his deep love for the institution in which he spent all his working life, his belief that many of the early contributions from Mt. Wilson have not been fully recognised and his deep anguish at Carnegie’s withdrawal from Mount Wilson in 1985. This history ends in the 1950s. Initially he had planned to put the later history into a second volume, but the effort of completing the 650 pages of the first sapped his energy, and he left only fragmentary notes for any sequel. He had already written articles on the first fifty years of Palomar. Hale’s farsightedness shines through the volume. With the new developments planned for Las Campanas, the future of his observatory is bright and well in keeping with his dictum “Make no small plans”.

THE MAN

Allan Sandage was a tall powerful courteous man with a ready smile and strong blue eyes. He had a natural presence and a slow incisive delivery. This, coupled with his encyclopaedic knowledge of astronomy and its history, made him a dominant participant in those conferences that he attended. These became fewer over the years; he preferred to work and find out things, rather than debate their reality. His attitude was that debates settle nothing except who is the best debater, and the true answer is always decisive evidence gained at the telescope.

Allan and Mary had two sons, David and John, and later three grandchildren. In most of the early years the family took camping holidays. They were all musical, and in the long nights in the 200 inch observing cage Allan liked to listen to opera, especially Wagner. The whole family particularly enjoyed the sabbatical year they spent on Mount Stromlo in Australia in 1968–69, when the boys travelled down to school in Canberra. They even extended their stay to 15 months. More recently they went on cruises, often down the Mississippi; these were sometimes timed so that Allan could avoid a conference or a meeting.
that he did not wish to attend. He had a strong conviction that the world with its natural laws was not created by chance and must be there for some purpose. He explored religion, but did not find it satisfied his quest for knowledge.

In his later years he withdrew himself into his work, in order to avoid debate and controversy. While this resulted in a phenomenal output of papers, to some degree it deprived the younger generation of knowing the fun, the charm and the historical perspective of a great astronomer. Diagnosed with pancreatic cancer in the Fall of 2009, Allan Sandage still managed to take his family on one last cruise to Hawaii, do research at home, and publish three first-authored papers during his last twelve months. He died on 13 November 2010, surrounded by his loving family, at his home in San Gabriel, California.

HONOURS AND AWARDS

In the inaugural year of the Gruber Prize for Cosmology two full prizes were awarded; one to Sandage was for Observational Cosmology. He received the Crafoord Prize of the Swedish Academy of Sciences in 1991, and the President’s National Medal of Science in 1971. Other medals were the Eddington (1963) and Gold (1967) medals of the Royal Astronomical Society, the Pope Pius XI gold medal of the Pontifical Academy of Science in 1966, the Franklin Institute’s Elliott Cresson medal (1973), the Bruce medal of the Astronomical Society of the Pacific (1975), and the Adon Medal of the Nice Observatory (1988). He was Russell Lecturer to the American Astronomical Society in 1973 and received their Helen Warner prize in 1960. He received the Tomalla Gravity prize of the Swiss Physical Society in 1993.

Sandage was elected to the US National Academy of Science in 1963, but resigned in 1980 when the Academy failed to elect his friend and collaborator Olin Eggen. He was a Member of the Lincei National Academy in Rome. He was elected a Foreign Member of the Royal Society in 2001. He had honorary degrees from at least eight different universities and colleges.

Finally, main belt asteroid 9963 Sandage, originally 1992 AN and discovered by Eleanor Helin, is named in his honour.

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Many sent us reminiscences of Allan Sandage; several we have used explicitly, the spirit of others we have tried to incorporate into the text. In particular we thank Mary Sandage for answering our questions and giving us details that only she knew. Allan’s greatest collaborator, Gustav Tammann, sent much, as did Owen Gingerich, Helmut Abt and John Kormendy. We thank Harden McConnell, Michael Feast, Tom Kinman, Ken Freeman, Vera Rubin, Rob Kennicutt, Harry Fergusson and Harry Nussbaumer for material that helped us. Sandage’s account of his road-trip with Baade was published in an article by Owen Gingerich in Physics Today 47, no. 12, pp. 34–40, 1994. The paragraph describing his reaction to the request that he take 200-inch plates for Hubble was taken from an oral history interview by Dr. Spencer Weart on May 22, 1978, at Santa Barbara St., Pasadena, California, which we found particularly useful in preparing this memoir. See interview with Dr. Allan Sandage, Niels Bohr Library & Archives, American Institute of Physics, College Park, Maryland, USA: http://www.aip.org/history/ohilist/4380_1.html
1952 (With M. Schwarzschild) Inhomogeneous stellar models. II. Models with exhausted cores in gravitational contraction. *Astrophys. J.* **116**, 463–476.

1953 (With H. C. Arp & W. A. Baum) The HR diagrams for the globular clusters M92 and M3. *Astronom. J.* **57**, 4–5.

The color–magnitude diagram for the globular cluster M3. *Astronom. J.* **58**, 61–75.

1956 (With M. L. Humason & N. U. Mayall) Redshifts and magnitudes of extragalactic nebulae. *Astronom. J.* **61**, 97–162.

1958 In *Stellar Populations*, Vatican Symposium, ed. D. J. K. O’Connell.

1958 The ability of the 200-inch telescope to discriminate between selected world models. *Astrophys. J.* **133**, 355–392.

1961 (With O. J. Eggen & D. Lynden-Bell) Evidence from the motions of old stars that the Galaxy collapsed. *Astrophys. J.* **136**, 748–766 (ELS).

1963 (With T. A. Matthews) Optical identification of 3C 48, 3C 196, and 3C 286 with stellar objects. *Astrophys. J.* **138**, 30–56.

1965 The Existence of a major new constituent of the universe: The quasi-stellar galaxies. *Astrophysical J.* **141**, 1560–1578.

1978 (With J. Kristian & J. A. Westphal) The extension of the Hubble diagram. II. New redshifts and photometry of very distant galaxy clusters: First indication of a deviation of the Hubble diagram from a straight line. *Astrophys. J.* **221**, 383–394.

1982 (With G. A. Tammann) Steps toward the Hubble constant. VIII. The global value. *Astrophys. J.* **256**, 339–345

1984 (With G. A. Tammann) The Hubble constant as derived from 21 cm linewidths. *Nature* **307**, 326–329.

1985 (With B. Binggeli & G. A. Tammann) Studies of the Virgo cluster. V. Luminosity functions of Virgo cluster galaxies. *Astronom. J.* **90**, 1759–1771.

1990 (With J.-M. Perelmuter) The surface brightness test for the expansion of the universe. I. Properties of Petrosian metric diameters. *Astrophys. J.* **350**, 481–491.

1999 The first 50 years at Palomar: 1949–1999. The early years of stellar evolution, cosmology, and high-energy astrophysics. *Annu. Rev. Astron. & Astrophys.* **37**, 445–486.

(With A. Saha, G. A. Tammann, L. Labhardt, F. D. Macchetto & N. Panagia) Cepheid calibration of the peak brightness of type Ia supernovae. IX. SN 1989B in NGC 3627. *Astrophys. J.* **522**, 802–838.

2001 (With L. M. Lubin) The Tolman surface brightness test for the reality of the expansion. IV. A measurement of the Tolman signal and the luminosity evolution of early-type galaxies. *Astronom. J.* **122**, 1084–1103.

2006 (With G. A. Tammann, A. Saha, B. Reindl, F. D. Macchetto, & N. Panagia) The Hubble constant: A summary of the Hubble Space Telescope program for the luminosity calibration of type Ia supernovae by means of Cepheids. *Astrophys. J.* **653**, 843–860.

2008 (With G. A. Tammann & B. Reindl) The expansion field: The value of \( H_0 \). *Astron. & Astrophys. Rev.* **15**, 289–331.

2010 The Tolman surface brightness test for the reality of the expansion. V. Provenance of the test and a new representation of the data for three remote Hubble Space Telescope galaxy clusters. *Astron. J.* **139**, 728–742.
(With B. Reindl & G. A. Tammann) The linearity of the cosmic expansion field from 300 to 30,000 km/s and the bulk motion of the local supercluster with respect to the cosmic microwave background. Astrophys. J. 714, 1441–1459.

Books

1961 The Hubble Atlas of Galaxies. Carnegie Institution of Washington.

1975 (With M. Sandage & J. Kristian, eds.) Stars and Stellar Systems. IX. Galaxies and the Universe. The University of Chicago Press.

1981 (With G. A. Tammann) A Revised Shapley-Ames Catalog of Bright Galaxies. Carnegie Institution of Washington.

1988 (With J. Bedke) Atlas of Galaxies Useful for Measuring the Cosmological Distance Scale. NASA SP–496.

1994 (With J. Bedke) The Carnegie Atlas of Galaxies. Carnegie Institution of Washington.

2004 Centennial History of the Carnegie Institution of Washington, Vol. 1: The Mount Wilson Observatory. Cambridge University Press.

Sandage was an Editor of the Annual Review of Astronomy and Astrophysics from 1990 Volume 28 to 2004 Volume 42.