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THE FIRST 50 YEARS AT PALOMAR: 1949–1999 The Early Years of Stellar Evolution, Cosmology, and High-Energy Astrophysics

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PROLOGUE

In 1999 we celebrate the 50th anniversary of the initial bringing into operation of the Palomar 200-inch Hale telescope. When this telescope was dedicated, it opened up a much larger and clearer window on the universe than any telescope that had gone before.

Because the Hale telescope has played such an important role in twentieth century astrophysics, we decided to invite one or two of the astronomers most familiar with what has been achieved at Palomar to give a scientific commentary on the work that has been done there in the first fifty years.

The first article of this kind which follows is by Allan Sandage, who has been an active member of the staff of what was originally the Mount Wilson and Palomar Observatories, and later the Carnegie Observatories for the whole of these fifty years.

The article is devoted to the topics which covered the original goals for the Palomar telescope, namely observational cosmology and the study of galaxies, together with discoveries that were not anticipated, but were first made at Palomar and which played a leading role in the development of high energy astrophysics.

The Palomar work first showed how optical astronomy would be the key to our understanding of observations made in other parts of the electromagnetic spectrum, particularly at radio wavelengths and at X-ray energies.

—*Geoffrey Burbidge, Editor*

■ **Abstract** An account is given of the history of two observational programs set for the Palomar 200-inch telescope, one by Walter Baade and the other by Edwin Hubble near the start of the scheduled operation of the telescope 50 years ago. The review is partly an assessment of whether, and how well, these programs have been carried to completion, and partly an account of the response of Palomar to new discoveries and

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developments not foreseen in 1950. Stellar evolution, the discovery of variations in the metallicity of stars of different populations, the chemical evolution of the Galaxy, the Cepheid P-L relation, the redshift-distance relation of the expanding universe, and the extragalactic distance scale are discussed as they relate to the predictions for progress on the programs set out by Baade and Hubble. Not foreseen was the invention and development of radio astronomy and high energy astrophysics, leading to the discovery of radio galaxies, quasars, and the gradual realization of violent events, both in stars and in galaxies. The review is highly restricted to these subjects, covering only three areas among the totality of the work in observational astrophysics studied during the first 50 years at Palomar.

1. THE BEGINNING

The 200-inch Palomar reflector, shown in the famous drawing by Russell W. Porter in Figure 1, was commissioned for regular scheduled observations on November 12, 1949, fifty years to the month of the distribution of this volume of Annual Reviews. The Hale telescope, planned since 1929, had enormous publicity surrounding both its construction and the hopes for astronomy as to what it might accomplish. The purpose of this review is to discuss the extent to which those hopes have been realized. Palomar, together with Mount Wilson in the joint operation known at first as the Mount Wilson and Palomar Observatories, often lead the way in the explosive developments that have characterized astronomy in the period.

The formal dedication of the Palomar Observatory and of the Hale telescope took place on June 3, 1948, led by Vannevar Bush, president of the Carnegie Institution of Washington, and Lee Du Bridge, president of the California Institute of Technology.

A scientific dedication took place a month later during the joint meeting of the Astronomical Society of the Pacific and the American Astronomical Society (Richardson 1948). The principal scientific address was by Walter Baade (1948) titled “A Program of Extragalactic Research for the 200-inch Telescope.” This was a prescient document, outlining a research program that was to take 30 years. Much of Baade’s lecture will be discussed later.

The telescope was not released to the astronomers for another 16 months. Ira Bowen (Figure 2), hero of that period and for the following two decades, keeping his head when all others were losing theirs, knew that if he released the telescope to the astronomers, even for a few months, he would never get it back. As director and as one of the world’s foremost experts on optics, he was responsible for bringing the telescope to as high a state of perfection as the design of the engineers permitted.

By 1948, two problems had surfaced (Bowen 1948, 1949). (*1*) The lever system that grabbed the honeycomb ribbings at the back of the five-meter mirror had too much friction by a factor of 30 to keep the mirror at its proper figure for all gravity loadings. (*2*) As it left the optical shop, the mirror had a slight turned-up edge, purposely, so that its sag in the cell beyond the radius of the back squeeze levers

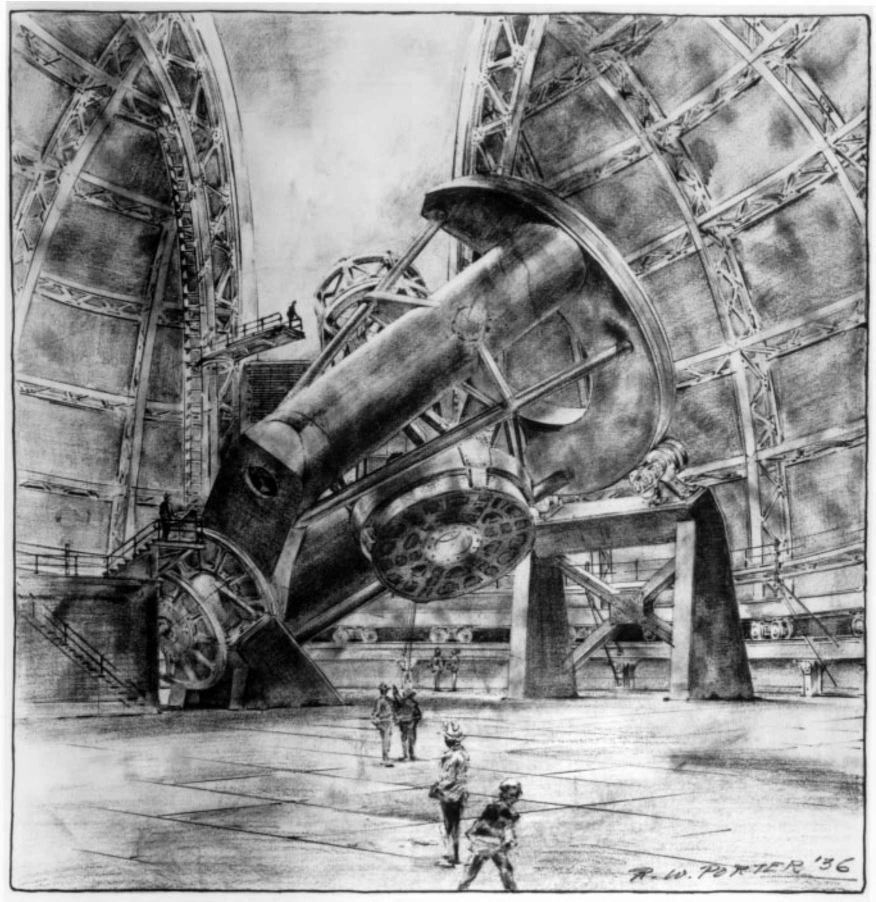

Figure 1 Drawing by Russell W. Porter of the 200-inch telescope and its dome made in 1936. Note the roller bearings at the north pier, replaced in the real telescope by the oil-pad flotation invention. Note also that the girders of the dome structure are not covered here as they are in the dome. The dome was finally completed with a double sheathing for thermal control.

was expected to compensate for the raised outer 20 inches. But the mirror did not compensate as was predicted. It was too stiff.

Thus, Bowen made the very difficult decision to take the mirror out of the telescope and polish down the turned-up edge on the dome floor. The final figuring of the outer raised 20 inches was done by Don Hendricks, the chief optician of the Mount Wilson observatory who had a magical touch, together with Mel Johnson, one of the opticians who had originally worked on the mirror from 1936 to 1946 in the Caltech optical shop (with four years out for World War II).

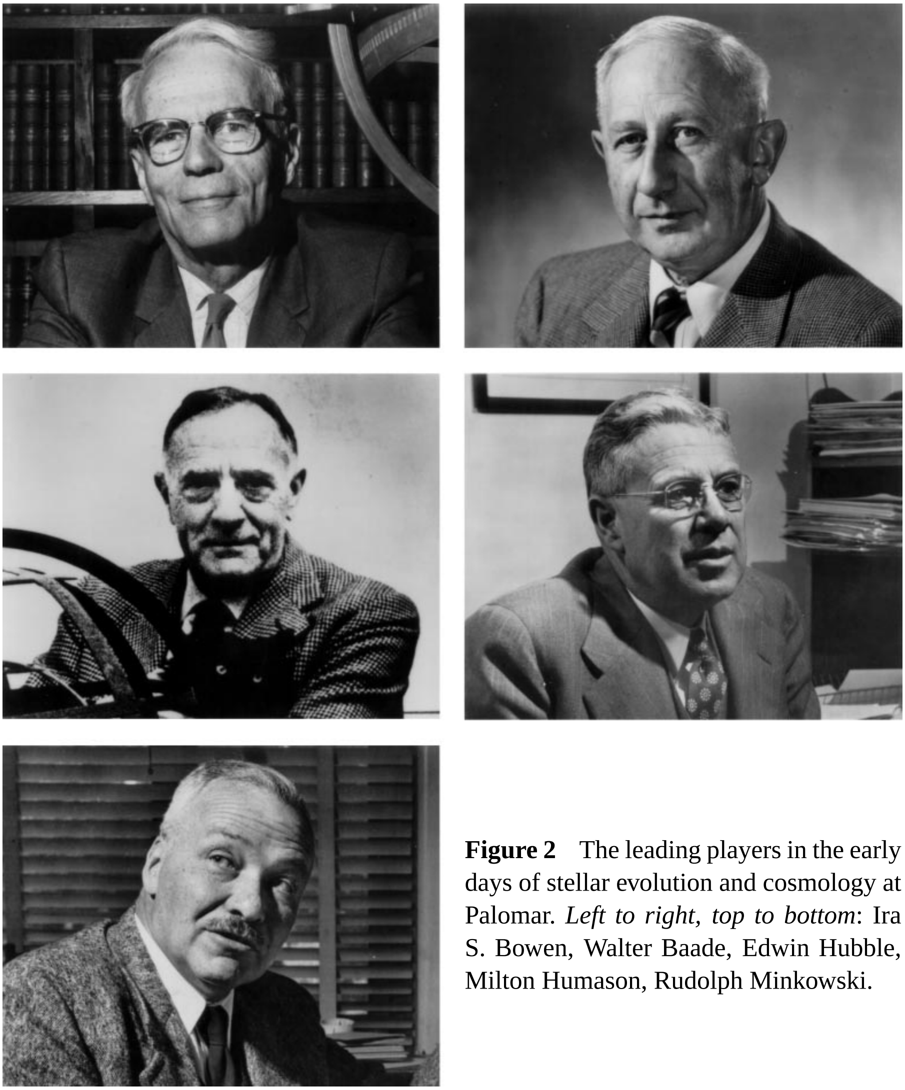

Figure 2 The leading players in the early days of stellar evolution and cosmology at Palomar. *Left to right, top to bottom*: Ira S. Bowen, Walter Baade, Edwin Hubble, Milton Humason, Rudolph Minkowski.

A long series of optical tests were made after this fix and were analyzed by Bowen from measurements on the Hartmann test plates. They revealed that the mirror was nearly perfect. The matter-of-fact description of these trying tests and his initial decision to remove the mirror for the fix is described by Bowen (1950) in a classic paper entitled “Final Adjustments of the 200-inch Telescope.” He had waited to publish this account until Hubble (1949) had written an account called “First Photographs With the 200-Inch Hale Telescope” in which Bowen is not mentioned, yet the needed mirror correction is discussed as if the photographs had first revealed the problem. However, the first photographs had in fact been taken by Bowen with the telescope, months before, as part of the testing regime. As great an astronomer as Hubble was, he could never overcome his disappointment that he had not been chosen as the director of Palomar.

Nevertheless, Hubble's fame, importance, and close association with the 200-inch project through cosmology, which in some sense justified its construction following his seminal discoveries at Mount Wilson from 1922 to 1936, were the reasons he was given the opportunity to use the telescope in four observing runs between January 1949 and April 1949, interspersed with Bowen's Hartmann-testing regime.

The first scheduled run in which the telescope was officially assigned to an astronomer was on November 12, 1949. That observer was not Hubble. He had suffered a heart attack in June 1949 before the completion of Bowen's extensive work.

As important as the 200-inch reflector has been for astrophysics and cosmology, the Palomar wide field 48-inch Schmidt survey telescope was in some ways as important in the early years for mapping the northern hemisphere sky. That era is so long ago that it is difficult to remember the state of our ignorance of the deep sky before the Palomar Schmidt Survey. As it turned out, without that mapping, the 200-inch would have been vision impaired.

The primary 72-inch mirror for the big Schmidt had been completed by 1941 in the Mount Wilson optical shop. The difficult 48-inch correcting plate, ground and polished to its non-spherical figure by Hendricks, was completed in the summer of 1948 and the telescope went into routine operation in January 1949 (Bowen 1948). Walter Baade had been instrumental in bringing the principle of the Schmidt optical train back from Hamburg in the early 1930s, having been a colleague of Bernhard Schmidt, a taciturn Estonian, in the late 1920s when Baade was still on the staff of the Hamburg Observatory. They had been members of the Hamburg eclipse expeditions to Lapland in 1927 and the Philippines in 1929, and were close friends.

The first official Schmidt plate (recorded in the record book on September 29, 1948) was taken by Hendricks, who was in charge of the completion of the optics and collimations of the telescope. The 14-by-14-inch plate was of M31, seen for the first time on a single plate with superior definition and faint limiting magnitude in its full 4° extent. A reproduction of the Hendricks' plate is in Panel 18 of the Hubble Atlas (Carnegie Publication No. 618). The first published photographs from the 48-inch Schmidt were by Minkowski (1949) who showed them in his description and analysis of the nebula surrounding the young galactic cluster NGC 2244.

Four wondrous books on Hale and the making of the Hale telescope, of Palomar itself, and of its predecessor observatories of Yerkes and Mount Wilson are *The Glass Giant of Palomar* (Woodbury 1940), *Explorer of the Universe: A Biography of George Ellery Hale* (Wright 1966, 1994), *Palomar: The World's Largest Telescope* (Wright 1952), and *The Perfect Machine* (Florence 1994).

2. THE EARLY YEARS

Today astronomy and astrophysics is vastly different than it was in 1950. Although at that time much of the astrophysics of the stars was known through the spectacular advances in the basic physics (reviews by Stromgren 1951, Chandrasekhar 1951), little was yet understood about origins or evolution or the grand synthesis involving stars and galaxies that dominates the current climate. In that period the emphasis was on physical processes (see Aller 1956, Osterbrock 1974 for reviews of the physics of gaseous nebulae following Menzel, Aller, Goldberg, and Baker in the 1940s), classification systems, absolute magnitude calibrations (cf. Adams et al 1935 for the HR diagram), and surveys for the extant types of astronomical objects. Furthermore, observational cosmology had only just begun with galaxy classification, proof that galaxies and their distribution form the last great hierarchy in the organization of matter, and that the expansion exists (Hubble 1925, 1926a, 1926b, 1929a, 1929b, 1934, 1936a, 1936b, 1936c; cf. Sandage 1998b).

All this was the prelude to the 50 years that has now just ended. The tremendous change that we have witnessed can only be compared with the paradigm shift in geology and biology in the Darwinian era of the 1850s and the developments in relativity and quantum physics from 1900 to 1940. Astronomy's turn has been the last half century.

Of course, Mount Wilson and Palomar were not the only places where the first great advances into the new astronomy would take place, but the Observatories did have an enormous advantage in the first twenty years of Palomar. Radio astronomy hardly existed in 1950 and X-ray astronomy was not to be for 15 years. The first orbiting Astronomical Observatories (OAOs) were not operational until 1969. Computers had just been invented using von Neumann's concepts of stored programs.

In addition, most of today's large telescopes did not exist before approximately 1970. Those in existence before 1970 were not highly productive until after the 1960s. Hence, in 1950, Mount Wilson, Palomar, Lick, and Yerkes and McDonald were still the major centers of observational astronomy and astrophysics in America, with Radcliffe (Pretoria) and Stromlo just beginning in the southern hemisphere.

In this review I cannot cover even a fair fraction of the research done in the past half century, either at Palomar or worldwide. This account is necessarily highly restricted to stellar evolution, observational cosmology, and the beginnings of high energy astrophysics. It is primarily a retrospective on the programs set for the Palomar telescopes by Baade and Hubble 50 years ago.

2.1 The First Palomar Discoveries

Among the first of the interesting discoveries that often made the newspapers, even in the 1950s, occurred at Palomar during the initial trials with the 48-inch Schmidt prior to the beginning of the National Geographic-Palomar Sky Survey mapping.

Baade, having estimated how many asteroids were brighter than 19th magnitude,[1] discovered a fast moving asteroid on a Schmidt plate on June 26, 1949. It turned out to have a highly eccentric orbit whose perihelion distance was smaller than that of Mercury. It passed within 17 million miles of the sun, and within four million miles of the earth near the time of discovery (Richardson 1949, 1965). Because its perihelion distance was closer to the sun than any of the planets, Baade agreed to the name of Icarus.

It was the type of discovery that the public could understand, even if its cosmic importance did not rival the more central discoveries made soon thereafter. Nevertheless its significance for solar system astronomy and tests of general relativity soon became evident. The variations in its orbital parameters can be used to determine the mass of Mercury and the advance of the line of apsides due to space-time curvature caused by the solar mass (Herrick 1953, Gilvarry 1953, Dicke 1965, Francis 1965).

2.1.1 Stellar Evolution and Observational Cosmology

When the astronomical history of this century is written, the two central advances that will be cited 400 years from now are (*1*) the final understanding of stellar evolution as summarized by the HR diagram, and (*2*) the understanding of the universe as a whole through the development of observational and theoretical cosmology. Work with the 200-inch dominated both of these fields.

Our understanding of stellar evolution has progressed through the interaction of theoretical advances in studies of stellar interiors with the observational results concerning stellar populations, as defined by Baade (1944a, 1944b) in his resolution of the centers of M31, NGC 205, NGC 147, and NGC 185.

The population concept had crystallized in Baade's mind between 1939 and 1944, following the crucial clue provided by the discovery of globular clusters in the Fornax dwarf dE galaxy. In his many teaching sessions with H.C. Arp and this writer between 1949 and 1953, Baade was explicit in making the connection between the resolution into stars (Baade & Hubble 1939) of the main body of the Fornax dwarf and in its globular clusters. The Fornax globular clusters resolved into stars at the same apparent magnitude as the resolved stars in the main body of the Fornax dwarf itself. Thus it was natural to connect the HR diagram of globular clusters (Baade's population II) with the previously unresolved central region of M31 and also in the early type dE galaxies NGC 147 and NGC 185 whose stars were postulated to be of the same type as in the body of the Fornax dwarf.

A review of this approach by Baade to his population concept through the Fornax dwarf and then to contrasting the HR diagrams of globular clusters and of open clusters has been given elsewhere (Sandage 1986).

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[1] He did this following a rebuff by the IAU on the naming of an asteroid for his wife. The excuse of the name givers, following an early IAU convention, was that only Greek names could be used for asteroids, but Baade sometime in the 1930s set out to show that there were not enough Greek names to accommodate his estimate of appx.10^5 asteroids brighter than $m = 19$.

2.2 Baade's Program Proposed

Hubble's distances to M31, M33, and NGC 6822 depended both on the absolute magnitude calibration of the P-L relation of classical Cepheids and the accuracy of their apparent magnitudes. Both parts of this dependence were uncertain in 1948.

Baade discussed both of these problems in his paper at the July 1, 1948 scientific dedication of the 200-inch. Among other points he said:

> "Our first concern will be the extension of the magnitude scales down to magnitude 22.5, the limit attainable with the 200-inch. . . . With the photoelectric cell at the 200-inch, we . . . shall be able to reach magnitude 18.5, leaving to photographic photometry the faint end from 18 mag, to 22.5 mag. which can be comfortably bridged in a single step."

The most fascinating part of his lecture is:

> "Unfortunately . . . there remains considerable uncertainty regarding the adopted zero point of the period-luminosity relation of the Cepheids. . . . We intend to derive the zero point both of the Cepheids and the cluster-type variables in an entirely [new] manner. There is every indication that beginning with spectral type F the dwarf branches in the populations I and II coincide. To mention just one piece of the evidence: the dwarfs nearer than 10 parsecs with well determined trigonometric parallaxes are scattered along the same line in the Hertzsprung-Russell diagram whether they are slow moving stars or are of the high-velocity type. Hence by extending the H-R diagram in a globular cluster like Messier 3 to dwarfs of solar brightness we shall be able to connect directly the cluster-type variables with G dwarfs, the mean absolute magnitudes of which are ultimately based on well-determined trigonometric parallaxes. We thus obtain the mean absolute magnitude of the cluster-type variables. Now with the 200-inch we shall be able to reach in the Andromeda nebula the cluster-type variables (and the long-period variables associated with the population II). Since we know their absolute magnitudes, a comparison with the classical Cepheids in the outer spiral regions will furnish the absolute magnitude of the latter."
>
> ". . . Now we do not expect that this program, simple and straightforward as it may seem, can be carried out within the next three to four years, if necessary by resorting to so-called hard work."

In this last sentence, Baade was pointing out the importance of rare excellent seeing, rare enough that the work will be slowed because of it. But what actually happened is that the precept that the population I and II main sequences coincide (which was assumed by Baade) is not correct because of chemical composition differences—a difference not dreamed of in 1948.

When variations in the chemical compositions of stars did become apparent, a new program was required to solve the many problems caused by such variations. Those solutions were to occupy us for the first 20 years, and yet today, certain of the calibrations are still in doubt (many would say controversial). They include (*a*) the precise position of the main sequence as a function of metallicity, (*b*) the putative effect of chemical composition variations on the absolute magnitudes of the classical Cepheids (Sandage, Bell, Tripicco 1999), and (*c*) even yet, the absolute magnitude calibration of the RR Lyrae variables (Sandage 1993a, 1993b; Reid 1999).

The story I tell next is how Baade (1952) concluded even from his first observations of M31 with the 200-inch that the Cepheid P-L relation that was first calibrated by Hertzsprung (1913), copied by Shapley (1918), used by Hubble (1925, 1926a, 1929a), and apparently confirmed by Wilson (1939), was undoubtedly too faint by about 1.5 magnitudes.

2.2.2 Baade's Program Realized

The four parts of the program outlined by Baade (1948) were (*a*) redetermine the magnitude scales to m = 22.5, (*b*) recalibrate the Cepheid P-L relation by the new method that was, (*c*) to find the main sequence of globular clusters and calibrate therewith the absolute magnitudes of RR-Lyrae variables, and (*d*) discover RR-Lyrae variables in the disk of M31 to compare with the apparent magnitudes of the M31 classical Cepheids, thus calibrating them.

All parts of this program were eventually carried out using both the Palomar and Mount Wilson telescopes. Much was learned in the process about stellar evolution, the chemical evolution of the Galaxy, methods to age-date the stars, and the relation between kinematics and chemical composition among the different stellar populations.

First Revisions of the Magnitude Scales Made at Mount Wilson In the 1930s Baade had been engaged in redetermining the faint magnitude scales in particular Selected Areas of the original Kapteyn program (cf. Blaauw & Elvius 1964). He had found significant magnitude scale corrections to the Mount Wilson Catalog of Photographic Magnitudes in Selected Areas (Seares et al 1930). However, although Baade's photographic photometry had shown the urgent need for corrections to the Mount Wilson Catalog fainter than $m_{pg} = 16$, more accurate results could be obtained using the new photomultiplier cells developed during the war. At the request of Baade and Hubble, Stebbins, Whitford, and Johnson (1950) began a photoelectric campaign to test the faint magnitude scales of the Mount Wilson Catalog and the North Polar Sequence (Seares 1922).

Their important 1950 paper had a profound effect in showing that the Mount Wilson scales needed corrections at the faint end beyond m = 16 that sometimes reached 1.5 mag at m_{pg} (Seares) = 19. The result was a sober realization that a vast work in precision photometry for cosmology and stellar population studies lay ahead. That work, once begun, was to occupy the next 30 years.

Later Revisions of the Magnitude Scales at Mount Wilson and Palomar A program of photoelectric photometry to determine faint magnitude sequences was begun soon after the 200-inch was operational. W.A. Baum, an excellent experimental physicist, was appointed to the Carnegie staff to begin the work. Baum (1946) had worked in the rocket group led by Richard Tousey at the U.S. Naval Research Laboratory. With this experience and the photometric expertise he had gained in his Caltech PhD thesis in measuring the extinction of the atmosphere near the 3000 A cutoff, Baum came to the Observatories as the resident photometrist.

He supervised the construction of a prime-focus focal plane, pulse-counting photometer (Baum 1953) and started a program of three-color photometry of particular Selected Areas that were of importance for the galaxy programs of Hubble and Baade. Eventually, photometric sequences were determined to $B = 22$, well beyond the limit of the Mount Wilson Catalog.

Although never published, Baum's magnitude sequences in SA 61, SA 68, and SA 57 were used internally for many years at the Observatories for various programs where photographic transfers were still used to calibrate particular fields.

However, after about 1970 the observing programs that required photometry were planned around the modern practice of establishing photoelectric sequences directly in the fields of interest. Nevertheless, it is still of interest to determine the general level of corrections needed to the Mount Wilson Catalog even as bright as $m = 18$. To this end, the Selected Area program begun by Baum was continued into the 1980s using both the Mount Wilson and Palomar telescopes. The results for the 11 Selected Areas of SA 28, 29, 45, 55, 57, 71, 82, 94, 106, 107, and 118 are now in the literature (Sandage 1999).

The two main reasons why Hubble's extragalactic distance scale needed the large revision that is now nearly completed were (*a*) all his magnitude scales fainter than $m_{pg} = 18$ were too bright by as much as 2 mag at his limit, and (*b*) his adopted Cepheid P-L calibration was too faint by 1.5 mag.

2.2.3 Baade's Factor of Two in the Distance Scale

Failure to Resolve the RR Lyraes in the Disk of M31 Hubble's (1929a) distance modulus of M31 was $m - M = 22.0$. Baade (1944a) revised Hubble's modulus to $m - M = 22.4$, based on his preliminary revision of the Mount Wilson Catalog magnitudes in Selected Area 68, but still using Hubble's adopted zero-point of the Classical Cepheids.

The assumed absolute magnitude of RR Lyrae variables was $M_{pg}(RR) = 0.0$ at that time, based on the most recent calibration by Wilson (1939). This apparently confirmed an earlier statistical parallax determination by Bok and Boyd (1933). Wilson's analysis combined the more recent and more accurate proper motions with radial velocities of 55 RR Lyraes measured by Joy at Mount Wilson. Therefore, the calibration by Wilson of both the classical Cepheids and the RR Lyrae absolute magnitudes seemed secure.

Consequently, if $m - M = 22.4$ for M31, and with $M(RR) = 0.0$ for the RR Lyraes, Baade should have resolved RR Lyrae variables in the disk of M31 near the 200-inch plate limit of $m_{pg} = 22.5$. Even more telling, the giant branch of the M31 globular clusters should resolve easily beginning at $m_{pg} = 21$. Their absolute magnitudes were believed to be $M_{pg} = -1.5$ ($M_{vis} = -2.8$) according to the HR diagrams known at the time (Baade 1944a, Figure 1).

What Baade actually observed is described in the report of IAU Commission 28 for the Rome meeting (Hoyle 1952):

> "Baade then went on to describe several results of great cosmological significance. He pointed out that, in the course of his work on the two stellar populations in M31, it had become more and more clear that either the zero-point of the classical cepheids or the zero-point of the cluster variables must be in error. Data obtained recently—Sandage's colour-magnitude diagram of M3—supported the view that the error lay with the zero-point of the classical cepheids, not with the cluster variables."

Following a request by Shapley for Baade to expand on the evidence, Baade replied, again at the Commission 28 IAU session:

> "According to the present zero-points we should expect to find the cluster variables of the Andromeda nebula at $m_{pg} = 22.4$ since the distance modulus of this system, derived from the classical cepheids, is $m - M = 22.4$. The very first exposures on M31, taken with the 200-inch, showed at once that something was wrong. Tests had shown that we reach with this instrument, using the f/3.67 correcting lens, stars of $m_{pg} = 22.4$ in an exposure of 30 min. Hence, we should just reach in such an exposure the cluster-type variables in M31, at least at their maximum phases. Actually we reach only the brightest stars of population II in M31 with such an exposure. Since, according to the latest colour-magnitude diagrams of globular clusters, the brightest stars of population II are photographically about 1.5 mag. brighter than the cluster-type variables, we must conclude that the latter are to be found in M31 at $m_{pg} = 23.9$, and not at $m_{pg} = 22.4$ as predicted on the basis of our present zero-points.
>
> "We have also convincing proof that the brightest stars of population II in M31 are properly identified because when they emerge above the plate limit the globular clusters in M31 begin to be resolved into stars. It should be emphasized that these are rough first data indicating the order of corrections which the present constants require."

To make these points secure was to occupy the next 20 years at Palomar.

Although Baade's public announcement was not made until the Rome meeting of the IAU in 1952, Hubble (1951) had already discussed Baade's discovery in his Penrose Lecture before the American Philosophical Society in April 1951.

He wrote:

> "But now we find that something is wrong somewhere. The luminosities assigned to the Cepheids led us to expect that the globular clusters in M31 would be readily resolved with the 200-inch, and that their brightest stars, as

> well as comparable stars in the main body of the nebula, could be studied individually with ease. It was found, however, that the stars in question were fainter than expected by a considerable fraction of a magnitude, and that they could be recorded and studied only with difficulty. The discrepancy is important because M31 has been explored on the basis of Cepheids while our system has been explored, in a sense, on the basis of globular clusters."

The Route Through Globular Clusters: Discovery of the Main Sequence Baade organized the work in two parts. First he began a long campaign on the Cepheids in M31 itself, mounting a discovery program for variable stars in four fields at varying distances from the center. He invited Henrietta Swope, a Harvard expert in photographic photometry, to join him in the analysis of his 200-inch plates. A first summary of the Cepheids found in the inner three fields is given by Baade & Swope (1955).

By 1963 Swope had completed the analysis of the crucial outlying Field IV (Baade & Swope 1963) where the absorption and crowding is minimal. Baade and Swope used a local photoelectric sequence that had been measured by Arp with the 200-inch and published as part of the Baade-Swope paper. A well-defined P–L relation was found in B and V. The mean magnitudes of the Cepheids ranged from $B = 20.5$ to 22.8. These data, together with the new Cepheid P–L calibrations by Arp (1960a) and by Kraft (1961), which we discuss in a later section, gave distance moduli of 24.84 in B and 24.68 in V. These are close to the modern value of $(m - M)_o = 24.44$ (Madore & Freedman 1991) as corrected for $E\ (B\text{-}V) = 0.10$ mag reddening.

The second part of Baade's program was to tie the classical Cepheids to the RR Lyraes via observations in the disk of M31. As was discussed earlier, this required discovering the main sequences of globular clusters and fitting the resulting HR diagrams with the main sequence stars with known trigonometric parallaxes. The vertical fit of the fitted HR diagrams calibrated the luminosities of all the cluster stars, including the RR Lyrae variables.

The latter was the problem Baade posed to Arp and this writer, his two graduate students at the time. Baade proceeded to train us well in the then extant large-telescope techniques of observing on the Newtonian platforms of such telescopes as the Mount Wilson 60-inch at first, and later at the 100-inch Hooker reflector. Using plates of M92 calibrated by photographic transfers to Selected Areas 61 and 57, close to the two target globular clusters of M92 and M3, we just reached the main sequence in M92 near $V = 19$.

Near the end of the two-year observing program we were joined by Baum who supplied a photoelectric calibration of our photographic sequences, and therefore of all the cluster stars in M92.

At the same time, Baade had taken a series of plates of the cluster M3 in B and V to carry the work to the limit of the Palomar telescope. The M3 main sequence was reached easily, and the photometry could be extended for several magnitudes beyond the turn-off point. With the main sequences in two globular clusters now identified, we were confident enough to announce the result at the Cleveland meeting of the American Astronomical Society at a symposium on the HR diagram (Arp, Baum, & Sandage 1952; ABS). The details for both clusters were published a year later (ABS, 1953; Sandage 1953).

We made the fit of the M92 and M3 main sequences to the main sequence of the nearby trigonometric stars in the manner suggested by Baade in his 1948 lecture. Our result that $M_V(RR) = 0.0$ seemed to confirm Baade's conclusion, stated in Rome, that the error was not in Wilson's absolute magnitude of the RR Lyraes but rather that the distance to M31 must be larger than Hubble's (1929a) value. As a consequence the error must be in the adopted P–L relation of the Cepheids by the reasoning that Baade had set out at Rome. Baade's result is generally considered to be the first major discovery with the Palomar telescope.

But convincing as our main sequence fits appeared to be, the problem of calibrating the RR Lyrae variables was eventually found to be considerably more complicated. The positions of the population I and II main sequences in the HR diagram were soon shown not to be the same, contrary to Baade's assumption. Involved were (*a*) the central discovery of the chemical variations among the stars, (*b*) its meaning for stellar evolution and Galactic structure, (*c*) the relation of the discovery to the work by Burbidge et al (1957) on the formation of the chemical elements, and (*d*) the theoretical expectation and the observational proof that the luminosity of stars at a given temperature depends on the metallicity, i.e. that main sequence positions are functions of [Fe/H].

This was all heady stuff at the time. The daily excitement, fervor, and transcendental character of the work, together with its promise for a cosmological synthesis of origins and astronomical evolution in the broadest sense, is impossible to describe. All who lived through the development from 1950 well into the 1980s will recognize these years as being as close to ineffable perfection as a scientific life can get.

3. STELLAR EVOLUTION

3.1 Stars Move Off the Main Sequence Rather Than Up or Down

With the discovery of the main sequence turn-off of the globular clusters and the heretofore unseen connection of the main sequence to the subgiant and the giant branches, the path of stellar evolution had suddenly become clear. Stars move off the main sequence rather than either down or up it as they age. Although trivial now, it was a revelation in 1952.

By 1940 it was well known that the main sequence could be explained as the locus of stars with different fractions of hydrogen throughout a chemically homogeneous stellar interior. Hence, a fully convective star, mixing the products of hydrogen burning uniformly throughout its interior, will progressively increase the mean molecular weight of its gas owing to the progressive increase in the helium content, and will move up the main sequence (Gamow 1940, Figure 36; Oke & Schwarzschild 1952, Figure 3; Bok 1946; Stromgren 1952). Likewise, stars on the bright part of the main sequence will move down the sequence if they lose significant mass as they age.

Even as late as 1946, these two processes were believed to be the keys to an understanding of the HR diagram and the time-dependent evolution of stars (see Section 8 of Bok 1946). Stromgren (1952) also discussed the process. Soviet astronomers continued to discuss the process even into the 1960s (Ambartsumian 1952; Massevich 1954, 1959; Fessenkov 1952; Fessenkov & Idlis 1959). Cowling (1958) provides an excellent review.

However, with the discovery of the globular cluster main sequence, its turn off near $M_V = +4$, and the identification of the turn-off with the Schonberg-Chandrasekhar 10 percent mass limit for a hydrogen exhausted isothermal core (Schonberg & Chandrasekhar 1942, Sandage & Schwarzschild 1952), it had become clear that a mapping off the MS was the principal feature of the evolution. This mapping also gave a satisfactory explanation of Trumpler's (1925) system of classification for the variety of HR diagrams of open clusters, and his related discovery of the turn-up of the main sequences of open clusters near their MS termination points (Oke 1955; Sandage 1958a,b, 1988).

3.2 The Chemical Composition Connection

A most significant development in the decade of the 1950s was the emergence of what is now perhaps the most important idea in stellar evolution and whose ramifications cover parts of cosmology as well. The mantra, summarized from its various versions, would read:

> "The chemical elements heavier than H and He are made in stellar interiors and are spread throughout the interstellar medium by supernovae explosions. Because this is a continuous process, the metallicity of all stars subsequently made from the ISM will increase with time. Hence, on average, the oldest stars will be metal deficient compared with newly forming stars. The age–metallicity relation is expected to vary from place to place. Study of metallicity as a function of age, kinematics, and position can give clues to the problem of the formation of the Galaxy in particular, and the chemical evolution of galaxies in general, at all redshifts."

The opening campaign to reach this advanced form of the mantra was first set out by Hoyle (1946, 1954 in his Figure 1). The Hoyle program was, of course, brought to its classic maturity in the monumental paper by Burbidge et al (1957, B^2FH), from which the concept took flight. A proper history of how the ideas of varying metallicity and its implications, as developed by the early 1960s, requires a separate article. Here, we simply give the barest of the historical highlights of how, within less than two decades, the subject of the chemical evolution of cosmic objects grew into the present maelstrom. For the purposes here, the theme is to show only why our early main-sequence fits were incorrect. The history in greater detail has been given elsewhere (Sandage 1986, Sections 4 and 6).

The early study that began the study of variations in the chemical abundances of stars was by Chamberlain and Aller (1951). They analyzed Mount Wilson 100-inch high dispersion Coude spectra of the extreme subdwarfs HD 140283 and HD 19445, finding metallicity deficiencies of factors between 6 and 10 relative to the sun.

The famous underground story,[2] often told, is that the referee of the paper was so astounded that he disbelieved the factor of approximately 100 originally derived by Chamberlain and Aller.

It is said that the referee suggested that their stellar temperatures should be adjusted upward so as to decrease the metallicity deficiencies. Chamberlain and Aller did this partially, and finally published metallicities of [Fe/H] $= -0.8$ and -1.0 for HD19445 and HD 140283 respectively (their Table 8). But even they were astounded at this result. They wrote:

> "The one possible undesirable factor in our interpretation is the prediction of abnormally small amounts of Ca and Fe. As Greenstein suggests, the observed deficiency of some elements could possibly be caused by an *excess* second ionization—i.e., much higher ionization than that predicted by the Saha formula."

Hence, even as late as 1951 there was no clear idea of the extent (or even the existence) of gross deviations of the chemical abundances relative to the sun. However, the Chamberlain & Aller paper was the beginning of the current remarkable era of abundance analyses (see McWilliam 1997 for a review). Their paper was followed by Burbidge & Burbidge (1956) where the abundance variations, taken by them to be real, began to be put in the context of chemical evolution of the galaxy. The later detailed analysis of HD 140283 by Baschek (1959) using high dispersion plates taken in 1957 with the Mount Wilson 100-inch Coude spectrograph by Unsold, was definitive and gave [Fe/H] $= -2.32$. The value was closely confirmed by Aller & Greenstein (1960) using new, highly widened plates taken both with the Mount Wilson and the Palomar Coude spectrographs.

In the meantime, Roman (1954) had made the central discovery of the general ultraviolet excess in the spectral energy distribution of particular high-velocity stars. In a prescient paper she had isolated a homogeneous group of 17 "ultra" high-velocity stars that had ultraviolet excesses (relative to the UBV two-color locus defined by stars of low velocity with the same B-V colors) reaching 0.2 mag in delta U-B. The excess UV radiation was suggested by Stromgren (unpublished) to be due to lower Fraunhofer line absorption shortward of 4000 A in the spectrum,

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[2] The nearly universal opinion of the time was that there was a fixed chemical composition of all stars throughout the universe, a kind of cosmic palimpsest containing some hidden initial, but universal, mystery relating to origins and evolution.

presumably due to lower metallicity. This was shown to be the case for less extreme metal deficiencies (Schwarzschild et al 1955). A model with the introduction of “blanketing lines” in the UBV two-color diagram (Sandage & Eggen 1959) generalized the case. Roman (1955) greatly added to the study of the UV excess for high velocity stars for which she had made a catalog that contained both photometric and kinematic data.

The first calibration of the UV excess in terms of the [Fe/H] metallicity deficiency was made by Wallerstein & Carlson (1960). They used the small number of abundance analyses that were just coming from the stellar abundance program of Greenstein and his team of postdoctoral fellows, using both the Mount Wilson and the Palomar Coude spectrographs. Wallerstein (1962) made a later calibration of the UV excess/metallicity relation that has been widely used because of the much larger number of calibrating stars it contains. Examples of the early literature are the papers by Helfer et al (1959), Wallerstein (1962), Wallerstein et al (1963), Wallerstein & Greenstein (1964), and Wallerstein & Helfer (1966).

The slope of the blanketing lines in the UBV two-color diagram was calibrated by Wildey et al (1962) based on high dispersion spectrograms obtained by the Burbidges with the Mount Wilson 100-inch Coude. A table of blanketing-line slopes and the resulting corrections to colors was made using the Wallerstein (1962) calibration of the excess itself. Later, account was taken (Sandage 1969) of the effect of the guillotine on the observed excess due to the convergence of the slope values of the blanketing and intrinsic lines in the U-B, B-V diagram for subdwarfs redder than B-V = 0.7. A normalized UV excess was defined, as reduced to B-V = 0.6, to account for the guillotine. Subsequent calibrations of the normalized UV excess include those of Carney (1979) and Cameron (1985).

After Roman’s discovery of the UV excess in the 17 field high-velocity subdwarfs, the same type of excess was sought in globular cluster stars. It was soon found in the giant stars of the cluster NGC 4147 (Sandage & Walker 1955), and soon thereafter in M3 (Johnson & Sandage 1956), M13 (Baum et al 1959), M5 (Arp 1962), and M15 and M92 (Sandage 1970a). This closed the last test for the identification of the field high-velocity F and G stars with stars in globular clusters that had been suggested by Baade (1944a), based on Oort’s (1926) PhD thesis on high-velocity stars.

As a consequence, the work also established the great age of the field subdwarfs because, from the age-dating of the globular clusters (Sandage & Schwarzschild 1952) it was known that these clusters, as a whole, were as old as the first stars formed in the galaxy. By extension, this identification led naturally to the model of the formation of the galaxy through collapse from a larger volume (Eggen et al 1962, Sandage 1990a).

With the knowledge gained that there is a large difference in the metallicity between globular cluster stars and the common field F and G stars of the population I, we became aware, but only gradually, that our initial fit of the globular cluster main sequence to the nearby trigonometric field stars discussed earlier was not correct. The suspicion was that the MSs of metal-poor subdwarfs were fainter than the population I MS by a progressive amount that depends on [Fe/H].

In hindsight, it turns out that the first evidence of that fact was in fact the position of HD 19445 and HD 140283 in the HR diagram of Adams et al (1935) where these two stars were among the six "intermediate white dwarfs" found in the Mount Wilson spectroscopic catalog of 4367 spectroscopic parallaxes (look carefully at their diagram: the six outriders at spectral type near A5 and absolute magnitude near +5 are easily missed).

The second reason to suspect an offset between the population I and II MSs was theoretical. Stromgren (1952) had set out homology relations from stellar interior theory that showed that MS stars of low metal abundance are expected to have fainter MS positions than those of higher metallicity. Although now a well-known proven proposition, the premise had not been proved observationally or indeed by calculated stellar models (rather than homology transformations) even in the mid 1950s. The first calculated model with zero metals was by Reiz (1954), where his model star was indeed a star lying fainter than the high metallicity MS (i.e. it was a subdwarf).

Recall that all we had to work with in the 1950s were stellar parallaxes that were sufficiently inaccurate for the few very high velocity field stars that the observational test for the existence of a faint subdwarf sequence was uncertain. However, analyzing the available data on less extreme stars that had only mild subdwarf characteristics (intermediate velocities and small but definite UV excesses), we could provide an observational proof of sufficient weight that was almost convincing that a relation does exist between UV excess and depression of the MS from that of the population I high metal stars (Sandage & Eggen 1959, Figs. 1 and 2).

However, the extreme case for the very low metallicity stars, similar to those in globular cluster stars, was only given by the moving group parallax of the Groombridge 1830 group (Eggen & Sandage 1959), a result not widely accepted at the time.

The problem of the MS position was discussed again three years later using the totality of known trigonometric parallaxes and the rapidly growing data on UBV photometry of the trigonometric parallax stars. By combining these data we could show that the departure from the main sequence of F and G stars was a progressive function of [Fe/H] (Eggen & Sandage 1962), reaching the order of 1 mag departure faintward for subdwarfs with [Fe/H] $= -2$. From this calibration, a new MS-fitting procedure could be used, as illustrated for the fit to M13 in Figure 10 of the cited paper (Eggen & Sandage 1962). Later fits were made (Sandage 1970a), the most complete being of 19 cluster diagrams to the continuum of MS positions as a function of [Fe/H] (Sandage & Cacciari 1990).

With this development, the RR Lyrae stars could now be calibrated by the MS fits, bringing to a close, in principle, that phase of Baade's Palomar program originally proposed in 1948. The most recent use of the method is reviewed by Reid (1999), based on post-Hipparcos analyses of the relevant new trigonometric parallaxes.

4. CALIBRATION OF THE CEPHEID P–L RELATION

Baade's plan to recalibrate the zero-point of the Cepheid P-L relation using the difference in apparent magnitude between the Cepheids and RR Lyrae stars in M31 (Baade 1956a) was frustrated by the strong dependence of M(RR) on [Fe/H] just discussed. The calibration of the effect is still in contention at the 0.3 mag level, and until the calibration of M(RR) is beyond doubt, Baade's route to the Cepheid P-L calibration will remain uncertain.

Remarkably, an independent method of calibration of the P–L relation of classical Cepheids came into play in 1958. Peter Doig (1925) first pointed out that the Cepheid U Sgr was probably a member of the galactic cluster M 25. Irwin (1955) rediscovered this fact, which, together with Eggen's knowledge that NGC 7790 contains three Cepheids, opened the way to use photometric parallaxes of the parent open clusters to calibrate the Cepheids.

A program of photometry and spectroscopy was begun by Arp, Kraft, and the present writer in 1958, both at Mount Wilson and at Palomar, to obtain the necessary data on distances and reddenings to carry a new calibration of the P–L relation to a preliminary conclusion.

By 1961, six calibrators had been completed—CF Cas (Sandage 1958c), EV Sct (Arp 1958), DL Cas (Arp et al 1959), CV Mon (Arp 1960b), U Sgr (Sandage 1960, Johnson 1960, Wampler et al 1961), and S Nor (Irwin 1958, Fernie 1961). Kraft (1961) discussed all of the photometry of the parent open clusters that existed to 1961, redetermining the cluster reddenings and distance moduli on a uniform basis.

Kraft's new reductions, plus four additional long-period Cepheids in the h and chi Per complex adopted as members on the basis of Eggen's (1965) discussion, were used in a calibration of the P–L relation whose shape was redefined by combining relative relations from M31, NGC 6822, LMC, and SMC (Sandage & Tammann 1968). The double Cepheid CE Cas a and b in NGC 7790 was added later (Sandage & Tammann 1969) following the difficult photometry of the individual components that are separated by only 2.3 arcsec.

The resulting 1968 zero-point, based on only nine fundamental calibrators is, remarkably, within 0.02 mag of the recent Hipparcos zero-point as defined by Feast & Catchpole (1998). It is also brighter by between 0.07 and 0.10 mag than the Feast & Walker (1987) calibration, which itself is an average of 0.11 mag fainter than the Hipparcos calibration (Sandage & Tammann 1998, Seggewiss 1998), suggesting a small systematic error in that calibration of order 0.1 mag.

Hence, the 1961 and 1969 Cepheid calibrations fully supported and refined Baade's 1952 discovery of the error in the previous calibrations from Hertzsprung (1913), to Shapley (1918), to Wilson (1939). Hence, by 1970 Baade's 1948 program was complete.

The dream of the astronomers at the Palomar dedication in 1948, expressed with conviction by Vannevar Bush in his address "Two Observatories Operate as One," had in fact come true.

5. COSMOLOGY

Hubble had outlined his vision of cosmological research with the Palomar telescopes in his 1951 Penrose lecture. His principal plans concerned four programs:

(1) the large scale distribution of galaxies

(2) the law of redshifts

(3) the cosmic distance scale

   (a) Cepheid P-L relation

   (b) distance to M31

   (c) novae as distance indicators

   (d) distances to M81 group and M101 group galaxies

   (e) the "average" galaxy as a statistical distance indicator

   (f) brightest stars

   (g) brightest galaxies in clusters

(4) Cosmological theory

Many of these programs have eventually been carried to completion, yet the final solution of the distance scale remains at this writing in contention, even if only at the 25 percent level.

Other programs not mentioned by Hubble but which have also been central to the Palomar work concern Galaxy morphology as it relates to galaxy formation and evolution. Here Baade's population concept has become intertwined with Hubble's purely geometrical cosmology.[3]

In particular, the problem of the earliest stages of galaxy formation, not even conceived in the 1930s, is now centered on studies of the Lyman alpha forest that was seen in high dispersion quasar spectra, detected at sufficient spectral resolution by Weymann et al (1981). Many Palomar studies followed, where the telescope was host to the efficient instrumentation developed by the UK group led by Boksenberg and used in many collaborations with Caltech astronomers. Important reviews include those by Weymann (1993), Lanzetta (1993), Bajtlik (1993), Boksenberg (1995), and Rauch (1998).

How much of Hubble's program has in fact been completed?

5.1 Large-Scale Distribution

Hubble had dreamed of beginning at Palomar a galaxy count program of the type he had pioneered in the 1930s (Hubble 1934). The data had formed the basis of

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[3] Baade's dictum, often stated with vigor when, in his opinion, too large a fraction of the scheduled 200-inch time was being assigned to the redshift programs of Hubble and Humason, was "You will never understand the spatial geometry (world model) until you understand the galaxies that you are using as markers of the space."

his work with Tolman on world models (Hubble & Tolman 1935) and his famous analysis papers (Hubble 1936a,b) on the log N(m) relation (see Sandage 1998b for a review). To this end he began to accumulate plates in the spring of 1949 for galaxy counts with the 48-inch Schmidt camera. The very large 14-by-14-inch plates had exquisite definition over a 7° × 7° field compared with the Mount Wilson large reflector plates that covered only 0.25 square degrees which Hubble had used for the 1934 study.

My first association with Hubble and the research part of Mount Wilson and Palomar was as a summer assistant in 1949 in measuring the plates and beginning the galaxy counts. The program was not continued for several reasons, one of which was Hubble's heart attack in July 1949, and another was the press of the more urgent programs that Hubble had set out.

It is fortunate that the count program did not become a central project at Palomar because it would not have been carried to the necessary conclusions to have made a major contribution. Hubble acknowledges this in his Penrose lecture, stating:

> "The distribution of nebulae over the sky is not included in the Palomar program. Such an investigation is being carried on at the Lick Observatory by counting the nebulae on survey plates with the fine 20-inch camera which in time will cover the entire sky observable from that latitude. [The program by Shane and Wirtanen] will present the distribution of more than a million nebulae to about 18th magnitude. The data will test the current assumption of large-scale uniformity over the sky ('isotropy' or 'no favored direction') and will describe the small-scale distribution, or tendency toward clustering."

Indeed, the Lick survey did just that (Shane 1975).

The program on the large-scale distribution, although not done at Palomar, is central to modern cosmology and includes the early papers by Seldner et al (1977), Gregory & Thompson (1978, 1982), Chincarini & Rood (1979), and Tarenghi et al (1979), with reviews by Oort (1983) and Rood (1988).

A most important survey of galaxy distribution that was done at Palomar and that has had a lasting influence on observational astronomy is the catalog of galaxy clusters by Abell (1958, 1975). Abell's survey was made using the 48-inch Palomar Observatory–National Geographic Sky Survey plates (POSS) as his Ph.D. thesis from the California Institute of Technology, under the direction of Rudolph Minkowski, director of the Sky Survey. More will be said about this important Abell catalog in the next sections, but before leaving the large-scale distribution problem, it should be pointed out that Abell, already in 1959, anticipated the discovery of the filaments, sheets, and voids, which are now known to be present by his first identification of what he called superclusters, or clusters of clusters.

5.2 The Velocity-Distance Relation

5.2.1 The Mount Wilson Years

Following Hubble's announcement of the primitive form of a velocity-distance relation (Hubble 1929b), anticipated by Robertson (1928) and Lemaitre (1927, 1931), Humason began an extended program of redshift measurements with the Mount Wilson 100-inch Hooker reflector. By 1931 these data were combined (Hubble & Humason 1931) with apparent magnitude estimates to define a redshift-apparent magnitude relation for field galaxies and for the few galaxy clusters known at the time.

By 1936 Humason (1936) had carried the redshift data to 40,000 km s^{-1} using a total of 10 great clusters known at the time (found by serendipitous discoveries in other survey programs). These data permitted Hubble (1936b) to define a velocity–"distance" relation for clusters to what was the enormous redshift of $z = 0.13$ for the Bootis cluster. It was here that the analysis and further observations from Mount Wilson stopped in 1936, awaiting the completion of the 200-inch.

Hence, at the time of the 1948 Palomar dedication, the cluster redshift-magnitude relation was defined by only ten clusters, and the field galaxy data numbered fewer than 200 objects. Essentially no data existed on (*1*) the isotropy of the expansion (the same in all directions?), (*2*) systematic velocity deviations, if any, from a linear velocity–distance relation that is required in all expanding models where large-scale homogeneity is maintained throughout cosmic time, and (*3*) the coldness of the flow itself as measured by the mean random motion about the systematic linear expansion.

These and other problems are what Hubble either meant, anticipated, or implied in 1951 in his program to study "the law of redshifts." That study was to take 30 years at Palomar.

5.2.2 The Humason-Mayall Redshift Catalog and its Analysis

By 1935 Mayall, having designed and put into operation a fast spectrograph at the Lick Observatory for the 36-inch Crossley reflector, began a redshift program on the brighter Shapley-Ames (1932) galaxies, mostly of spiral type. At the same time, Humason continued his 1931 redshift determinations using spectrographs at the Cassegrain focus of the Mount Wilson 100-inch Hooker telescope. Humason and Mayall continued observations through 1941, and began again in 1945 at the close of World War II (see the dates in Table V of Mayall in HMS 1956).

Humason began his extended redshift program at Palomar immediately upon the commissioning of the 200-inch, using a highly efficient new solid-block Schmidt camera that had been designed by Hendricks (1939) and Hendricks & Christie (1939), and whose difficult optics were eventually made by Hendricks in the Mount Wilson optical shop (Bowen 1960).

By 1956, Humason had obtained redshifts of 472 field galaxies at Mount Wilson and at Palomar, and 152 galaxies at Palomar in 26 clusters whose redshifts had reached the remarkable value of $z = 0.2$ for the Hydra cluster.

Most of the distant clusters were new. As mentioned earlier, many had been found in the systematic visual scanning of the Sky Survey plates as they were brought down to Pasadena as the survey progressed. This special search for clusters by Humason and the writer is described by Bowen (1954). At the time of HMS, the Abell Catalog was yet several years in the future.

Once candidate clusters had been found on the deep Schmidt plates, 200-inch prime focus photographs of the candidates were taken to prepare for Humason's later 200-inch spectroscopic observations. Because even the first-ranked galaxies in most of these clusters were not bright enough to be seen on the spectrograph slit, the plates, taken several months prior to the spectrographic observations, were measured in Pasadena for coordinate offsets relative to bright stars that Humason could see. Using these "offset" coordinates, Humason could move the prime focus spectrograph with precision screws to the invisible galaxy whose redshift was sought. The offset plates also were made with star trails superposed on them, made by stopping the telescope drive so that the brighter stars would show trails, from which the precise cardinal directions at the position could be determined. All of this was necessary during the 20 years before television viewing came to a data room that was remote from the telescope itself.

Mayall had also determined redshifts for 300 field galaxies at Lick. There were 114 overlaps between the lists of Humason and Mayall, which, together with many duplicate measures of a given galaxy at each observatory, permitted a thorough evaluation of the accuracy of the redshifts.

In the meantime, Pettit (1954) had measured photoelectric magnitudes at the Mount Wilson 60-inch of most of the field galaxies in the two lists, with a few also measured by Stebbins and Whitford (1952), also at Mount Wilson. For the extensive list of Virgo cluster members, individual photoelectric magnitudes of large-diameter galaxies had been measured by Whitford (1936). Others had been measured by Bigay (1951).

The entire photometry was combined with the Humason and Mayall redshifts to discuss the velocity–"distance" relation (Humason et al 1956, HMS), but now with a much larger database than was available to Hubble (1936) and Humason (1935) in the decade of the 1930s.

The Hubble diagram (redshift versus apparent magnitude, corrected for aperture effects and for the effects of redshift), now for 18 clusters reaching 60,000 km s^{-1}, showed that the velocity–"distance" relation was indeed linear, as had been suspected from Hubble and Humason's earlier results. Linearity is, of course, the most fundamental requirement of the theory and all models if the expansion is real (Heckmann 1942). Every place in the manifold appears to be the center of the expansion, but only if the velocity–"distance" relation is linear. The importance of this linearity requirement is the reason why such a large effort was put into the observational proof at Palomar of linearity from 1950 to well into the 1970s.

Besides testing for linearity, the new feature of the work was the early attempt to obtain the second-order term (the deceleration) from the cluster data, but the result was clearly premature, requiring a much larger data sample.

Following Humason et al (1956), the work was then expanded to eventually include more than 100 clusters over many directions to test for isotropy and for deviations from a pure Hubble flow (Sandage 1970b, 1975).

5.2.3 The Expanded Palomar Program on the Hubble Diagram

It was clear that a large campaign on clusters was needed to search for any anisotropy in the expansion rate and to attempt to measure the second-order (deceleration) term in the Hubble diagram (Robertson 1955, Hoyle & Sandage 1956). The program was begun before Mattig (1958) had found the exact solution of the Friedmann scale factor valid for arbitrarily large redshifts (see Sandage 1995, 1998b).

The observational campaign to extend the Hubble diagram using a large sample of remote clusters lasted from 1955 into the 1980s. The beginning of the program and the results to 1969 were outlined in a progress report (Sandage 1970b). The principal limitation was again the discovery and subsequent photometry and spectroscopy of suitable remote galaxy clusters beyond the limit of the Abell Catalog and of the 1956 HMS program.

Candidate clusters were found by two methods. The first was to exploit the discoveries of clusters that contained radio sources. The second, described in Section 5.2.4, was again a search with the 48-inch Schmidt. We discuss first the radio sources.

By the mid-1960s a number of identifications of the radio sources in the 3CR Cambridge radio source catalog had been made with relatively bright galaxies. These were generally the first or second ranked E galaxies in clusters. Following the earlier work of Minkowski (1960), Schmidt (1965) had begun a 200-inch observing program in the early 1960s for the redshifts of many of the identified radio galaxies.

Photoelectric photometry was also begun on many of the clusters and radio sources then known. The observations were made with the 200-inch prime focus photometer for the faint sources. The brighter radio galaxies were measured with the two Mount Wilson reflectors.

The results were published from 1972 to 1975 in a series of eight papers. The theme of the program was to continue to test the linearity of the velocity-distance relation and its isotropy (the same in all directions?), and to attempt again a measurement of the second-order deceleration term. The contents of the papers are too detailed to describe adequately here. Table 1 gives an outline of the problems discussed in each paper.

5.2.4 The Extension of the Hubble Diagram to Higher Redshifts

By 1975 the available cluster candidates from the Abell catalog and from southern clusters and groups had been nearly exhausted for the high redshifts necessary to determine q_o. The redshift range was limited to less than $z = 0.5$, the largest being Minkowski's (1960) redshift for 3C 295. The conclusion from Paper VII was that $q_o = 1 \pm 1$, hardly a useful result.

TABLE 1 Summary of the eight papers of the Redshift Distance series

Paper	Subject	Reference
I	Distinction is made between metric and isophotal diameters. Method to correct aperture photometry to a standard metric diameter is derived as used in the remaining papers of the series.	Sandage (1972a)
II	Hubble diagram for 84 first-ranked galaxies in clusters is derived, including data from Peterson (1970a) and Westerland & Wall (1969). $q_o = 0.94 \pm 0.4$ derived. Evolutionary correction is discussed (see Sandage & Tammann 1983).	Sandage (1972b)
III	Hubble diagram of 128 radio galaxies shows the equality of $\langle M \rangle$ for 3CR radio galaxies with that of first-ranked cluster E galaxies. A form of the Spaenhauer (1978) diagram is first used to illustrate selection bias.	Sandage (1972c)
IV	Position in the Hubble diagram of QSO relative to first-ranked cluster galaxies is discussed with a two-component luminosity model with QSO as the central component combined with the distributed luminosity of the host E galaxy. Color decomposition is given of the two components. Model is tested by Kristian (1973). Veron-Cetty & Veron (1985) and Hewitt & Burbidge (1987) show the continuum of QSO luminosities relating QSO, N galaxies (Matthews et al 1964) with Seyferts and LINERS.	Sandage (1973a)
V	V-r colors introduced as a photometric system (Sandage & Smith (1963) that proved to be identical (Sandage 1997) to $(V\text{-}R)_J$ by Johnson (1964, 1965). Hubble diagram of first-ranked galaxies first given in r magnitudes.	Sandage (1973b)
VI	Deviations from the mean line of the Hubble diagram studied as functions of cluster richness, and Bautz-Morgan (1970) luminosity contrast. Debate on the meaning of the constancy of the luminosity function for the first few ranked cluster members as a function of cluster richness (Peebles 1969, Peterson 1970a, 1970b).	Sandage (1973c)
VII	Luminosity functions of first three ranked cluster E galaxies. Comparison of known luminosity functions (Abell 1975 from 1968, Rood 1969, Oemler 1974, Krupp 1974, Sandage 1976). Argument by Geller & Peebles (1976), Schechter & Peebles (1976), Oemler (1976), and Dressler (1978) based on cD galaxies (Matthews et al 1964, Morgan & Lesh 1965). q_o derived again.	Sandage & Hardy (1973)
VIII	Redshifts (Sandage 1978) given for part of the remaining galaxies observed from Stromlo necessary to complete the redshift coverage of the Revised Shapley-Ames Catalog (Sandage & Tammann 1981, 1987). Isotropy of the local velocity expansion field studied with the result that the Rubin-Ford effect does not exist (see Rubin et al 1976).	Sandage (1975a)

Two parallel programs to discover clusters more remote than those in the Abell catalog were then begun at Palomar. One was carried out by the writer and described in Westphal et al (1975), and the other was by Gunn and Oke (1975).

The first search was made with the 48-inch Palomar Schmidt using photographic plates taken on the fine grain IIIaJ and 127-04 red plates that had recently been developed at Eastman Kodak by Millikan. These plates reached 0.5 mag fainter than the Sky Survey plates. Thirty fields were surveyed with a total area of 1500 square degrees. About 200 new clusters were found which, together with the clusters found between 1952 and 1957 by Humason & Sandage (1957) and Bowen (1954, 1957) but not observed by Humason, constituted the sample that we began to observe with a new sky-subtracting digital spectrograph invented by Westphal et al (1975). No catalog was published.

The survey by Gunn & Oke (1975) was begun using the 48-inch Schmidt, but they also went to fainter magnitudes by making a blind photographic search with the Hale telescope, eventually covering 11.3 square degrees and finding thereby 76 faint clusters (Gunn, Hoessel, & Oke 1986). The catalog from this program, augmented by the search made by Hoessel with the Kitt Peak four-meter Mayall reflector, was eventually published by Gunn, Hoessel, & Oke (1986). It still contains today the faintest sample of clusters found by optical searches.

The photometry and redshifts from the first survey were published in three papers (Westphal et al 1975, WKS, Sandage et al 1976, SKW, Kristian et al 1978, KSW). In the final paper we could extend the Hubble diagram to $z = 0.75$. Many of the new clusters had measured redshifts between 0.25 and 0.50. From the measurements of the colors as a function of redshift, no evolutionary effects in B-V or V-R were detected (KSW 1978) at the 0.05 mag level over the entire redshift range. This result heavily constrains theoretical models of E galaxy evolution in the relevant look-back times to those with only passive evolution (Sandage 1961, 1963; Oke 1971; Wilkinson & Oke 1978; Sandage & Tammann 1983).

After 1975 the program was carried entirely by Gunn, Oke, and their students. A series of papers were published on all aspects of the Hubble diagram, confirming the correlations in Papers VI and VII (Table 1) of luminosity of first-ranked cluster galaxies with cluster richness and Bautz-Morgan types, and extending the work to larger redshifts. Not only did they find new distant clusters, but Gunn and Oke individually developed powerful new instruments for the 200-inch that benefited all observers.

Oke (1969) designed and oversaw the construction of a 32-channel spectrum scanner used at the Cassegrain focus of the 200-inch. Gunn designed and oversaw construction of two instruments that also saw major use. They were (*a*) a combined photometric and spectroscopic instrument named PFUEI for Prime Focus Universal Extragalactic Instrument (Gunn & Westphal 1981), and (*b*) the prototype instrument for the Hubble Space Telescope WFPC camera, called the "four-shooter," built for Palomar at Jet Propulsion Laboratory under the leadership of Gunn and Westphal (Gunn et al 1984).

In their first paper on the Hubble diagram, Gunn & Oke (1975) initiated a new technique for the reduction of the aperture magnitudes, restricting the final observed raw magnitude to a fixed metric aperture of 16 Kpc (for $H_o = 60$). They then corrected for aperture effect using a correction that depended on the slope of the growth curve at their standard fixed metric diameter. This method differs from the procedure invented in HMS and adopted in the Redshift-Distance series (Table 1) where a standard growth curve was used to correct aperture magnitudes to essentially "total" magnitudes (Sandage 1972a, Paper I). The procedure of Gunn & Oke has also been used in more modern times by Postman & Lauer (1995) in their study of first-ranked cluster galaxies. The small differences in the conclusions of KSW 78 and Gunn & Oke (1975) concerning q_o can probably be traced to these different reduction procedures, showing the extreme sensitivity of the conclusions to the minuteness of the q_o effect.

New photometry on the intermediate band photometric system of Thuan & Gunn (1976) of first-ranked cluster galaxies in many Abell clusters was set out by Hoessel, Gunn, & Thuan (1980, HGT). They solved for the deceleration parameter giving $q_o = -0.55 \pm 0.45$. This, of course, is an accelerating universe, indicating a finite value of the cosmological constant, but the errors are too large to secure the result. As part of the same program Hoessel (1980) presented the surface photometry determined from two-dimensional detectors then available, for the galaxies studied by HGT.

In a major study, Schneider, Gunn, & Hoessel (1983a, SGH) analyzed the Hubble diagram for redshifts between 0.04 and 0.3, using the CCD photometry from the previous data papers. They obtained results similar to those of Sandage & Hardy (1973, SH) which showed that there are systematic variations of the absolute magnitude of first several ranked cluster galaxies with cluster richness and Bautz-Morgan contrast class. The work was extended to the first three ranked cluster members by SGH (1983b) where they also confirmed the result of SH concerning cannibalism.

Hoessel & Schneider (1985) published their surface photometry of the first-ranked cluster galaxies done at Palomar, again confirming the previous correlations with cluster richness (their Figure 4) and Bautz-Morgan contrast class (their Figure 3).

An important advance was made by Gunn, Hoessel, & Oke (1986) with the publication of their extensive catalog of remote clusters, discussed earlier. The catalog lists 418 clusters whose redshifts range from 0.15 to 0.92. It has provided the candidate lists for many of the current programs on distant clusters (Postman et al 1996, Oke et al 1998, Postman et al 1998, Lubin et al 1998).

This long narrative of the Palomar program on the "law of the redshifts" shows the central importance of the Palomar 48-inch and the Hale 200-inch telescopes in the development of practical (observational) cosmology during the last 50 years. The fleshing out of the Hubble diagram by the many varied programs shows how Hubble's proposed program was in fact carried to a level that could not have been foreseen in 1951.

Hubble's penultimate program, (see Section 5), was the recalibration of the extragalactic distance scale, which we discuss next. We have no space to discuss his last proposed program of "Cosmological Theory," which in fact now fills many current textbooks such as Narlikar's (1983) exemplar.

6. THE EXTRAGALACTIC DISTANCE SCALE

6.1 The First Step from the Local Group to NGC 2403

By the end of Baade's 200-inch campaign on M31, Baade & Swope (1963) had determined its moduli to be $(m - M)_{AB} = 24.84$ and $(m - M)_{AV} = 24.68$, fully 2.7 mag larger than Hubble's (1929a) value.

In a program parallel to Baade's, Hubble started an observing program to discover Cepheids in galaxies just beyond the Local Group. The targets were galaxies in the M81 and M101 groups (Holmberg 1950), eventually narrowing to M81, NGC 2403, and M101. The principal observers were Hubble, Humason, and the writer, with occasional plates taken by Arp, Baum, and Minkowski.

By 1963, 59 variables had been found in NGC 2403, of which 17 were later confirmed to be Cepheids. Some 10 Cepheid candidates were found in M81 together with 24 normal novae and a number of luminous blue variables (LBVs) of the kind discussed by Hubble & Sandage (1953) in M31 and M33. No Cepheids were found in M101, although nine LBVs were discovered (Sandage & Tammann 1974c, Sandage 1983b) using the total plate material that extended from 1909 (with the Mount Wilson 60-inch) to 1963. The variables in M81 were considerably less conspicuous than those in NGC 2403. Consequently the data for NGC 2403 were the first to be analyzed.

The long collaboration between G.A. Tammann and the writer began in 1963, starting with the analysis of the 200-inch plates of NGC 2403. By 1968 Tammann had obtained light curves for the 17 Cepheids in NGC 2403, with periods between 87 and 20 days, and light curves based on a photoelectric sequence that had been set up in the field of the galaxy. The distance modulus was $(m - M)_o = 27.56$ (Tammann & Sandage 1968), based on the Cepheid calibration of the P–L relation discussed in Section 4.

The result was a major shock at the time because of its implied consequences for the revision of Hubble's "remote" distance scale, and therefore for the value of the Hubble constant. As late as 1950, Hubble's distance modulus for NGC 2403 was $(m - M) = 24.0$ ($D = 0.6$ Mpc). If we were right that the modulus was $(m - M)_o = 27.56$ ($D = 3.2$ Mpc), then even at the very local distance of NGC 2403, Hubble's distance scale would be too small by a factor of five. This was much larger than Baade's original factor of two, as well as the final factor of three from Baade & Swope (1963). Therefore, by 1965 it was clear that a much larger attack on the distance scale was necessary than had been anticipated in 1948. The program was expanded into what ultimately became the series of ten papers called "Steps Toward the Hubble Constant."

6.2 The Steps Series from NGC 2403 to the Global Expansion Field

The Steps series has been reviewed elsewhere (Sandage 1998a). Only a few aspects need be summarized here in Table 2, but with a few added comments.

The five distance indicators listed by Hubble were Cepheids, brightest stars, novae, average galaxy luminosities, and brightest cluster galaxies. These were all eventually used in the programs to determine the distances to M31, the M81 and M101 groups, and ultimately to galaxies farther away in the remote expansion field.

Cepheids and the brightest cluster galaxies, together with the Palomar and Mount Wilson programs to calibrate them, were described earlier. The Steps program added the new distance indicators of (*a*) the angular size of HII regions and the linear calibration of the first three largest, and (*b*) supernovae of type Ia. In addition, novae, brightest stars, and galaxy luminosity functions that calibrated the van den Bergh luminosity classes in late type spirals were used, thereby completing Hubble's (1951) list. A few details of the Steps series are given in Table 2.

The definitive solution to the distance scale problem via the traditional ladder approach has had to await the results of the Hubble Space Telescope (HST) for Cepheid distances of galaxies that have produced supernovae of type Ia. The reviews by Teerikorpi (1997), and Branch (1998), and the calibrations of SNe Ia at maximum light via Cepheids (Sandage, Tammann, & Saha 1998; Saha et al 1999) continue to favor the long distance scale with $H_o = 55 \pm 5$, although other solutions still occur in the literature (Madore et al 1998).

7. EARLY DEVELOPMENTS IN HIGH ENERGY ASTROPHYSICS

7.1 Initial Identification of Radio Sources

What would develop into the present major discipline of relativistic astrophysics began with the "rediscovery" of cosmic radio waves. The initial discovery of Jansky (1932, 1933, 1937, 1939), and the genius and tenacity of Reber (1940a,b, 1942, 1944) in advancing the discovery are too well known to again recount here.

However, the major advances came after World War II when radio telescopes were first brought into operation. For the history of this early period we can refer the reader to articles and books by Hey (1946, 1973), Hey, Parsons, & Phillips (1946), Moffett (1975), and Sullivan (1982, 1984).

The connection with Walter Baade and Rudolph Minkowski at Palomar came after several groups of radio astronomers began to detect discrete sources of radio emission that needed to be identified with optical objects in the sky. Interferometric measurements in Australia and at Cambridge, England led to the discovery of several strong sources. The first definitive optical identifications were made by Baade and Minkowski (1954a, 1954b) with the 200-inch telescope, based on radio data provided by Bolton and Stanley (1948) who found the diameter of the Cygnus

TABLE 2 Summary of the content of the ten papers of the "Steps Toward the Hubble Constant" series

Paper	Subject	Reference
I	Data on angular sizes of the first three largest HII regions are given in galaxies in the Local Group. Distance-degenerate effects are discussed.	Sandage & Tammann (1974a)
II	Identification and photometry of the brightest resolved stars are given in 11 nearby galaxies with known Cepheid distances. Later data of the same kind for M81 and M101 are in Sandage (1983a, 1984).	Sandage & Tammann (1974b)
III	The stellar content of M101 is given based on a long series of 200-inch photometrically calibrated photographs. The distance modulus of $m - M = 29.3$ is 11 times the distance of $m - M = 24.0$ given by Hubble (Holmberg 1950). Kelson et al (1996), with $m - M = 29.34$, confirms the Steps value. $H_o = 56 \pm 9$ km s^{-1} Mpc^{-1}.	Sandage & Tammann (1974c)
IV	Calibration of the absolute magnitude of the van den Bergh luminosity classes. Modulus of the Virgo cluster derived as $m - M = 31.45 \pm 0.09$. $H_o = 57 \pm 6$.	Sandage & Tammann (1974d)
V, VI	The quietness of the local velocity field is derived from the photometric distances of nearby galaxies compared with kinematic distances. Redshift data in Steps VI for Sc I galaxies to $v = 20{,}000$ km s^{-1} are combined with Zwicky et al (1961–1968) magnitudes to give a Hubble diagram requiring $H_o = 57 \pm 3$. Observational selection bias, using a form of a Spaenhauer diagram, was discussed for the first time.	Sandage & Tammann (1975a, 1975b)
VII	Virgo cluster distance modulus of $m - M = 31.70 \pm 0.08$ derived using Tully-Fisher method. $H_o = 50 \pm 4$.	Sandage & Tammann (1976)
VIII	Type Ia supernovae calibrated via brightest stars in IC 4182 gives $H_o = 50 \pm 7$.	Sandage & Tammann (1982)
IX	A new method is introduced to tie the Virgo Cluster redshift to the remote expansion field devoid of all local velocity anomalies. The method was later made more precise by Jerjen & Tammann (1993) and Federspiel et al. (1998). Virgo modulus derived as $m - M = 31.70 \pm 0.09$. $H_o = 52 \pm 2$.	Sandage & Tammann (1990)
X	Globular clusters are used to give a Virgo Cluster modulus revising an earlier value by Harris et al. (1991) who used an incorrect calibration of M_V (RR). Using the Oosterhoff–Preston-Arp period-metallicity relation for RR Lyrae stars (Arp 1955; Kinmann 1959) as calibrated from pulsation equations (Sandage 1990b,c, 1993b,c) gives $m - M$ (Virgo) $= 31.64 \pm 0.25$. $H_o = 57 \pm 5$.	Sandage & Tammann (1995)

source to be less than eight arcmin; Bolton (1948) who added to the list of discrete sources; Ryle & Smith (1948) with a good interferometric position of Cas A; Bolton, Stanley, & Slee (1949) who had an early good radio position of Virgo A; and Smith (1951) who provided a very accurate radio position that coincided with the Crab nebula.

The three principal competing radio astronomy groups were strong rivals, each attempting to play a dominant role in the highly charged identification game, but each trusted Baade and Minkowski to play fairly. These optical astronomers kept all the radio-source-position information, communicated to them privately, strictly compartmentalized. It is clear from the content of the 1954 papers by Baade & Minkowski that each radio group had sent their new radio positions to Pasadena before publication, permitting the optical identifications to be made using the Palomar 48-inch and 200-inch telescopes.

In the early 1950s Caltech began a radio astronomy program, and John Bolton, an English physicist who was leading a radio astronomy group at CSIRO in Australia, was invited to develop a Caltech radio observatory. Starting from nothing in 1954, he built the Owens Valley Radio Observatory.

But before choosing that radio-quiet site, Bolton mounted his first antenna on the Palomar grounds, some 500 yards west of the 200-inch dome. He had recruited from Australia Gordon Stanley and J.A. Roberts, and also attracted graduate students and postdoctoral fellows to begin a dominant research program at Palomar before the completion of the permanent site in Owens Valley.

At the beginning, Bolton and his associates were still radio physicists, not astronomers. This led to wonderful accounts of their early encounters with the astronomy of the celestial sphere. The same problems were encountered by Ryle and his colleagues in Cambridge. Baade told of times when he and Minkowski began receiving radio positions from England and Australia from the several radio physics groups. Minkowski would write back asking for the equinox used in reporting the positions, to which questions were asked back as to “what do you mean by the equinox?” Not only were the astronomers rapidly being educated in the new world of radio physics, but the radio scientists soon learned about the celestial sphere.[4]

What was the connection of this new radio astronomy with relativistic astrophysics and, as it turned out, again with Palomar? The connection came through

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[4] A story as remarkable as it is true, verified by those who worked regularly on Palomar mountain, is the day when Bolton aligned the polar axis of his equatorially mounted, temporary, 25-foot Palomar dish. The antenna could be adjusted in azimuth once the direction of true north was established. The alignment was accomplished one sunny day when Bolton pounded a stake in the ground near the antenna and watched the direction of the shadow as the sun rose toward noon. When his watch, set to Pacific standard time, read 12 noon, Bolton marked the line of the shadow and made his polar axis parallel to it, clamping the antenna azimuth adjustments home. It was soon thereafter that Bolton decided he should have a few astronomy postdoctoral astronomical fellows join the project. One of these was T.A. Matthews, a recent Harvard Ph.D., who later played such an important role in the discovery of quasars.

the fact that the bulk of the radio emission is incoherent synchrotron radiation emitted by high energy electrons (typical energies of approximately 1 Gev), spiraling in weak magnetic fields (approximately 10^{-3} to 10^{-5} gauss). The developments that led to that conclusion are well summarized by Ginzburg & Syrovatskii (1964).

If synchrotron emission is the predominant process, it requires that (1) relativistic electrons and magnetic fields be present in the objects that are parents to the radio sources, and (2) that parts of the radiation must be polarized. Concerning item (*1*), Ginzburg (1953) had shown that relativistic electrons must be formed continuously in the interstellar gas of the galaxy by collisions of relativistic protons, already known in the cosmic rays reaching the earth, on interstellar atoms. Furthermore, in a very important paper, Pikelner (1953) had emphasized that magnetic fields exist in the interstellar medium throughout the galactic system. Concerning item (*2*), polarization of the galactic radio noise was believed to have been measured by the Soviet radio astronomer Razin (1956, 1957).

The Russians had also predicted that if this theory was correct, it might be possible to detect linear polarization of the optical light which in a few cases might be emitted by the synchrotron process. They first applied the argument to the radiation from the Crab. Optical polarization was first discovered in the Crab Nebula (Vashakidze 1954, Dombrovsky 1954). Oort & Walraven (1956) then published what has become a classic paper on observations and theory of the Crab radiation, settling the question of the physical process. Subsequently, Baade (1956c) published exquisite photographs made with the 200-inch that dramatically showed the polarization. These photographs were analyzed by Woltjer (1957). The result showed that the Crab Nebula contains a significant magnetic field and a reservoir of relativistic electrons.

A second prediction was made by Shklovsky (1955) that the jet in the center of M87 (the radio source Virgo A) would show optical polarization demonstrating that the synchrotron mechanism was ubiquitous in galaxies as well as in galactic objects such as the Crab. Acting on Shklovsky's suggestion, Baade (1956b), using the 200-inch, discovered polarization in the jet of that galaxy using a polarizing filter and photographic plates.

The importance of the discovery and an analysis not only of the energetics but also of the origin of the relativistic electrons were set forth in an important paper by Burbidge (1956b). This was the second of a number of papers on the energetics of radio sources by Burbidge (1956a, 1958, 1959) who was by then a Carnegie Fellow of the Mount Wilson and Palomar Observatories. Burbidge was the first theoretician appointee to the Observatories fellowship program, beginning a long and distinguished career in activities connected in many ways with the Observatories and with Caltech.

7.2 The Discovery of Quasars and the AGN Phenomena

The discovery of quasars is too tangled a story to yet be described fully here. A summary of the principal events leading to the discovery of the redshift of 3C 273 is given in the important account by Schmidt (1975, from an original manuscript of 1969). Fuller accounts are given in the monograph by Burbidge & Burbidge (1967) and the reviews by Sullivan (1982, 1984), and Hartwick & Schade (1990).

Soon after the 3C and 3CR Cambridge catalogs of the brightest radio sources were published, efforts were made using interferometry to determine the angular sizes of the various radio sources. Particularly important for the quasar history was the long base-line interferometry made by the Jodrell Bank radio astronomers. The group, led by Henry Palmer, moved three portable cylindrical parabolic antennas with effective diameters of 28 feet over a number of baselines in England. They performed interferometry with the Jodrell Bank 250-foot antenna, measuring the fringe visibilities of more than 350 3CR sources. With baselines ranging from 2200 to 61,100 wavelengths (Allen et al 1962, Rowson 1962), they compiled a list of unresolved 3C sources whose angular diameters were smaller than one arcsec, and therefore had "brightness temperatures" larger than 10^7 K, a telling indication of nonthermal radiation (Palmer 1961). Also from these data, Allen, Hanbury Brown, & Palmer (1962) surmised that many resolved 3CR sources were double, following the previous demonstration by Hanbury Brown & Das Gupta that Cygnus A is double.

T.A. Matthews, a recent addition to Bolton's Caltech radio astronomy group, was fascinated with the possibilities of optical identifications of the 3C sources using the Owens Valley radio interferometer, composed of two 90-foot movable radio dishes. Matthews also had good communications with the Manchester group of Palmer, and he also knew of the long baseline work they were doing.

Palmer had given an account of the Jodrell Bank work at one of the first Texas symposia on high energy astrophysics, which Matthews also attended (circa 1959; my records are incomplete). At that meeting (or shortly thereafter) Palmer gave more details privately to Matthews, including a rather complete list of 3C sources that were unresolved at 61,100 wavelength separation. Palmer's list was a subset of the complete list published later by Allen et al (1962).

In late 1959 Matthews began a program of position determinations in RA, and supervised a Ph.D. thesis program by Read (1963) for declination positions. He also made a working list of positions determined by others, including those by the Palmer group. In 1960 Matthews suggested a collaboration with optical astronomers with access to the 200-inch to begin the final phases of an optical identification program. It was through the invitation of Matthews that I became involved in the optical identification program that was to last far beyond the quasar discovery era, until most of the 3CR radio sources had in fact been identified.

At first we concentrated on Palmer's list of unresolved sources at 61,000-wavelength baseline. There were at least 20 such sources on our initial observing list (which has been lost), all of which later turned out to be radio-loud quasars. I began to take plates with the 200-inch in 1959, centered on Matthews' radio positions. The plates were measured by Matthews in Pasadena, from which the first three star-like identifications of 3C 48, 3C 196, and 3C 286 (Matthews & Sandage 1963) had been made by early 1960. All three were abnormally blue in the ultraviolet as determined from photoelectric photometry begun with the 200-inch in 1960, showing that 3C 48 varied in intensity by 0.4 mag over a one year period.

The object also had a totally abnormal spectrum that I could not decipher. The rest (almost) is history, as set out by Schmidt (1975).

“Almost” refers to the crucial radio position determined from a series of lunar occultations by Hazard, Mackey, & Shimmins (1963) for 3C 273. This position permitted Schmidt to identify the optical image on one of the 200-inch plates that was in Matthews’ possession, which Matthews had evidently turned over to Schmidt. The Hazard et al position of the two radio components (one centered on the optical star-like object and the other at the end of the obvious jet) were accurate to 1 arcsec, making the optical identification secure.

The heroes of the quasar discoveries were clearly Palmer for his brilliant measurements with his Jodrell Bank colleagues of the radio angular diameters, Matthews for all aspects of the identification work and for the organization of the joint Owens Valley–Palomar collaboration, Hazard for the position of 3C 273, and Oke (1963) and Schmidt (1963) for their joint discovery of the redshift of 3C 273.[5,6]

Beginning in 1963 the quasar program became frenzied with the 3C 273 redshift discovery, not only at Palomar, but also at Kitt Peak, Lick, and Hawaii, with rivalry between all groups and within each group often leading to severe tension.

Quasars come in all radio and optical luminosities. The most luminous in both optical and radio absolute magnitudes turned out, in fact, to be those identified from the 3CR catalog, which is not surprising when understood based on the ideas of bias in flux-limited catalogs (e.g. Teerikorpi 1997).

After 1963, radio weak (or quiet) quasars were discovered (Sandage 1965). The least luminous of these in both optical and radio luminosity blend with the N galaxies discussed in an earlier section. The continuum continues to the Seyfert galaxies, and finally to the LINERS mentioned earlier.

After the first few identifications of objects in the 3CR radio catalog had been made, the program developed into an attempt to identify all objects in the catalog. It was known by 1970 that perhaps 25 percent of the 3CR sources were not visible to the plate limits of the Palomar 48-inch Schmidt, and a number of these were also not seen on routine exposures at the known radio position with the 200-inch. A review of the remaining problems up to 1974 was given by Kristian & Minkowski (1975).

To complete the work, a cooperative program was begun with Campbell Wade using the new three-element interferometer composed of three movable 85 foot

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[5] The breaking of the redshift code in the spectrum of 3C 273 was done by Oke and Schmidt together when they combined their wavelength data and realized that they were seeing the Balmer series.

[6] The joys of doing science are boundless. Sometime during the long subsequent campaign with Kristian to optically identify all the remaining 3C sources, I was in communication with D.O. Edge, lead author of the 3CR Cambridge Catalog. Although we had never met, we had written in earlier letters about something concerning 3C 273 (the correspondence is lost). Edge, who is a devout churchgoer, confided that indeed 3C 273 was the radio source he liked best. The reason was that 273 is the number of his favorite anthem in the Methodist Hymnal.

dishes at the National Radio Astronomy Observatory (NRAO) in Greenbank, West Virginia, to obtain highly precise radio positions, from which Kristian and the writer would measure deep 200-inch plates to attempt to complete the 3CR identifications. The program was highly successful (Wade 1970; Wade, Sandage, & Kristian 1970; Brosche, Wade, & Hjellming 1973; Kristian & Sandage 1970; Kristian, Sandage, & Katem 1974, 1978), providing exceptionally faint galaxy candidates for the spectrographic observers of the 1980s, mostly at Lick and Kitt Peak. The redshifts and subsequent photometry extended the Hubble diagram to the new limits that were achieved in the 1980s.

7.3 M82 and NGC 1275 as Prototypes of Starburst Galaxies and Other Violent Events

We conclude this review with a glimpse at a few of the most bizarre objects found over the years with the 200-inch and other large telescopes. The types of galaxies in this category are now commonplace as prototypes of violent processes, but were not so at their discovery.

The subject, which is also a part of the discipline of high energy astrophysics, was reviewed early by Burbidge, Burbidge, & Sandage (1963), where photographs of some of the unusual galaxies are shown and analyses of the physics given.

Most of the types now recognized (Seyfert galaxies such as NGC 1068 and NGC 4151), the new amorphous galaxy type characterized by M82, possible colliding or even merging galaxies as in NGC 1275, jets as in M87, and starburst galaxies, probably with M82 again as a prototype) were shown.

One of the more spectacular examples is the enormous outflow of material from the “starburst” galaxy M82, shown in a composite photograph in Figure 3. The photographs making up this composite were made with the 200-inch using special filters. The energetics in the M82 system have proved to be important in understanding the general class of starburst galaxies, which have been found to be ubiquitous.

We finally comment on either a new type of violent event or a radical type of starburst galaxy where “violent star formation” is taking place. The type examples are NGC 625, NGC 1569, NGC 1705, and M82 in which copious star formation is clearly taking place and in which one or more very bright compact (essentially unresolved) embedded objects exist. A new morphological galaxy class for the type was invented (Sandage and Brucato 1979), called “amorphous.” The class is illustrated in the Carnegie Atlas of Galaxies (panels 333–340) where descriptions of the many examples of the bright embedded objects are given.

The importance of these bright objects became apparent when high dispersion spectra were taken by Arp with the 200-inch of the two luminous knots in NGC 1569. The spectra show narrow absorption lines of hydrogen and a definite Balmer discontinuity, characteristic of supergiant stars of type A0. However, the luminosities of the knots are $M_B = -14$, showing that the objects are very young superluminous star clusters (Arp and Sandage 1985). They are probably protoglobular clusters, just formed and with their main sequences intact all the way

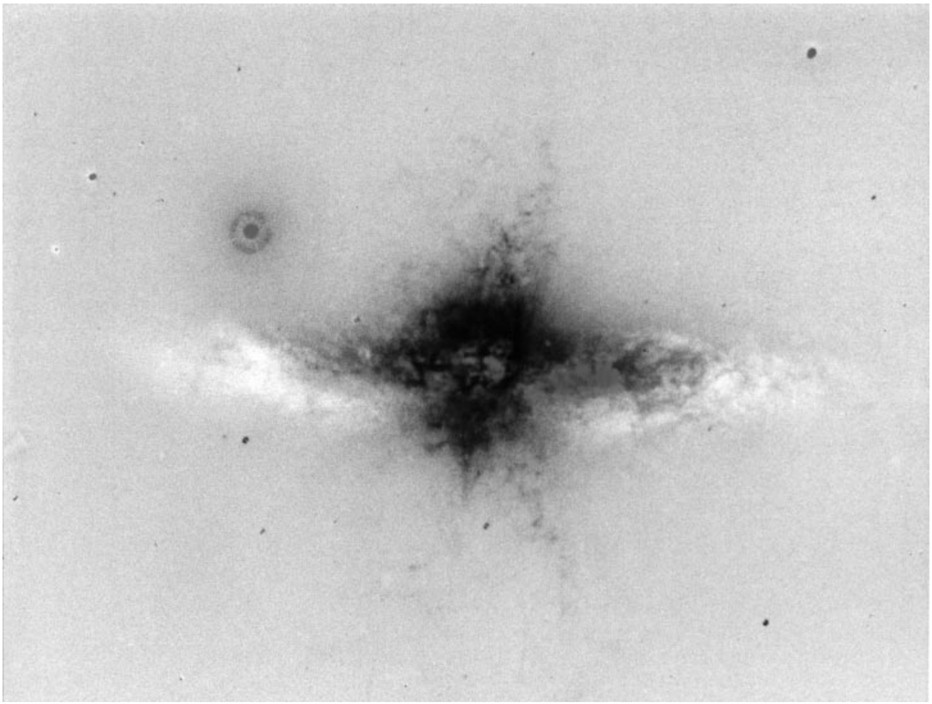

Figure 3 Composite photograph of M82 made by photographically subtracting a continuum image in broad-band yellow wavelengths, from a narrow-band H alpha photograph showing the H alpha emission strung along the minor axis. (Photograph from Lynds & Sandage 1963. Also in the Carnegie Atlas of Galaxies, Panel 333.)

to high luminosities. The phenomenon is ubiquitous in the amorphous types, as described in the Carnegie Atlas (Sandage & Bedke 1994).

The high-energy properties of the violent star formation in NCG 1705 and the formation of its supercluster at absolute magnitude near -14 in NGC 1705 is discussed by Mauer et al (1988, 1992). The two young globular clusters in NGC 1569 were known already in 1952 by Baade and by Hubble from their early 200-inch plates, but the ubiquitous character of the phenomenon has only recently become known, based on the Carnegie/Las Campanas morphological survey of Shapley-Ames galaxies that led to the Carnegie Atlas of Galaxies.

8. CONCLUSION

As a balanced account, this review is dreadfully incomplete concerning all that was accomplished at Palomar in its first 50 years. It has been organized in large measure by showing how the plans for research with the 200-inch telescope that were set out by Baade (1948) and Hubble (1951) were eventually completed—

slowed, to be sure, by the discovery of new subjects not even known when these giants walked the earth. Baade's prediction and final dictum in his prescient 1948 paper came to pass. He wrote:

> "We expect, therefore, that [the program outlined here] will spread over quite a number of years. At times it may even look as if it had been forgotten entirely because everyone is in hot pursuit of a new lead which opened up suddenly. But it will be carried out, because without a secure base we will go astray, and finally become lost."

Clearly, new leads were opened up, and the astronomers at Palomar and elsewhere were in hot pursuit. The result, seen in hindsight in these last months of the old century, is one of wonder, spectacular new understanding, and a knowledge of great accomplishment, made a reality by the insight of dreamers in the 1930s that made the great telescope possible.

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