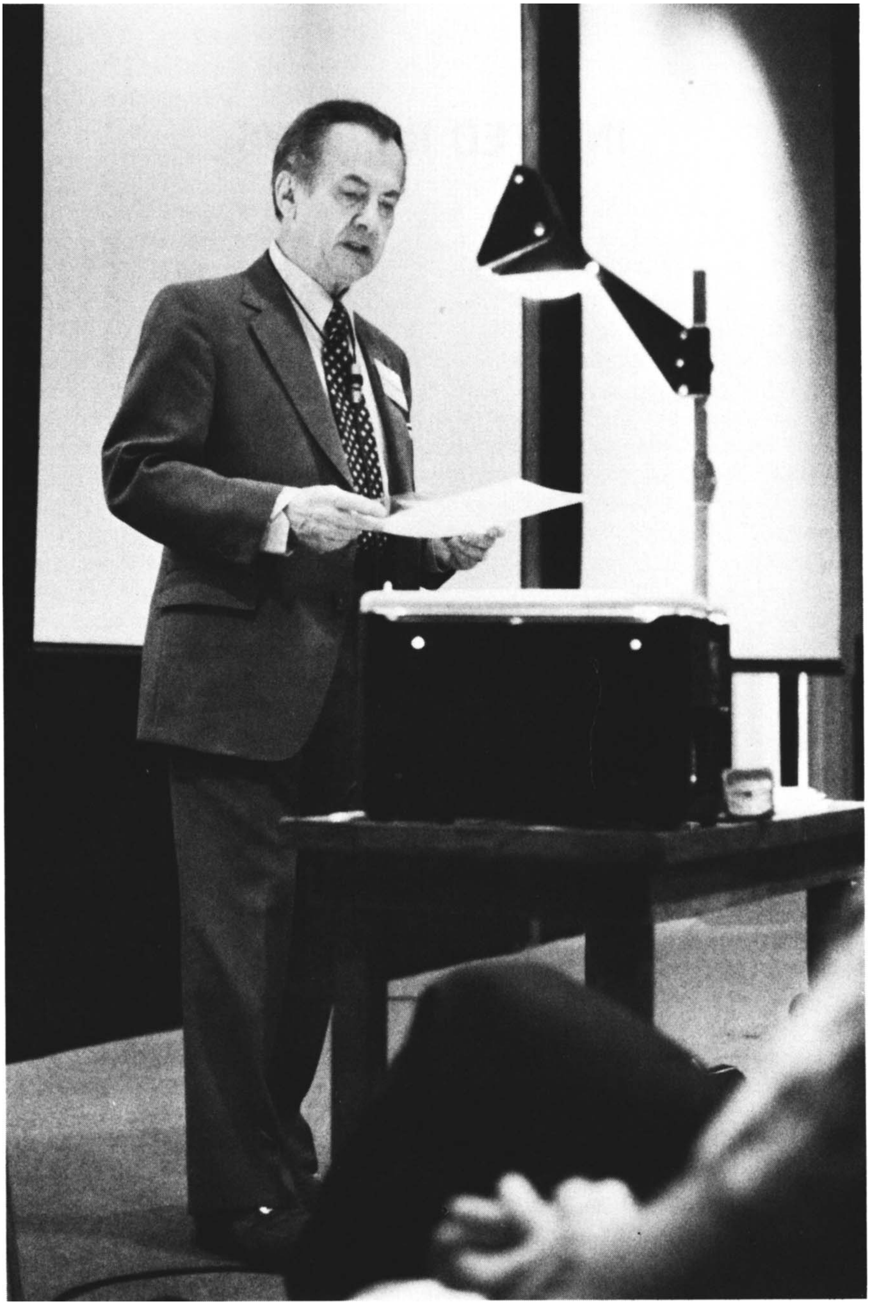
INVITED REVIEWS



G. de Vaucouleurs presenting the introductory review.

GENERAL HISTORICAL INTRODUCTION

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ABSTRACT. A brief historical review of the discovery and exploration of elliptical galaxies in the past two centuries is presented.

The organizers of this symposium have asked me to review the history of research on the nature and composition of elliptical galaxies as an introduction to and a background for current and future studies. For the reasons of space and perspective this review will not include the research of the past ten years or so, which other communications are bound to cover in greater detail.

1. PRE-HISTORY: FROM 1749 TO 1924

The brighter companion of the Andromeda nebula was discovered by Le Gentil on October 29, 1749. He estimated it to be 1′ in diameter. Charles Messier first saw it in 1757, judged it to be 2′ in diameter in 1764, and included it as No. 32 in his famous catalogue (Messier 1771, 1781). He also published the first drawing of it (Messier 1807), a fine engraving of M31 and its two companions, the second of which had been discovered by Caroline Herschel in 1783 and included by William Herschel as Nr V.18 in his first catalogue (Herschel 1786).

The designation "elliptic" was first applied to non–spiral nebulae by Stephen Alexander (1852). His discussion does not explicitly describe them as stellar systems, but includes a fine description of their various degrees of concentration and quotes a remarkable observation of John Herschel who noticed that their ellipticity decreases toward the center and that, irrespective of the ellipticity of their outline, many have semi–stellar globular nuclei.

The first attempt, that I know of, at describing the apparent brightness distribution in an elliptical nebula was made by Bigourdan, in the course of his micrometric "Observations de Nébuleuses et Amas Stellaires" with the 30–cm refractor of Paris Observatory. In 1890 and 1891 he described the bright semi–stellar central condensation of M32, 3″ to 5″ in diameter, and the smooth fading outward of the surrounding nebulosity, which he illustrated by two small sketches. He noticed that the central nucleus, which he compared to a star of magnitude 10.5 or 11, did not remain as sharp as stars of the same magnitude when the field was illuminated. Observing the center of M31 in 1899 with the same instrument he also noted that

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its nucleus, about 5″ to 6″ in diameter, "is much less stellar and much fainter than that of M32" (Bigourdan 1900).

The first successful attempt at measuring the luminosity profile of the central part of the Andromeda nebula by photographic photometry (within $\pm 7'$ from the center) was made in 1912–13 by Reynolds, who used his 28–inch reflector and a Hartmann visual microphotometer (Reynolds 1914). Under the, then common, misconception that the nebular might be diffuse material reflecting the light of a central star (the existence of reflection nebulae had been demonstrated by V. M. Slipher in the previous year), Reynolds tried to represent the "light curve"—as he called it—by an inverse square law, $x^2y = const.$, that is, in more familiar notation, $I = I_0/r^2$. It did not work. He then tried a simple modification, $(x+1)^2y = const.$; the modified formula, in which we recognize the familiar form, $I = I_0/(r+a)^2$, worked quite well! Since this formula is asymptotic to the inverse square law at large distances, Reynolds concluded that it supported the basic assumption of light scattering from a central source and thus conflicted with the concept of the nebula as an external galaxy! The relevance of Reynolds' work on M31 to the subject of this conference is, of course, that this same formula was later adopted by Hubble to represent the luminosity profiles of a representative sample of elliptical nebulae which he studied in his early years at Mt. Wilson, but published only in 1930 (see below).

The first spectrographic observation of M32 was made in 1913 by Slipher, with the 24–inch *refractor* of Lowell Observatory (Slipher 1914, 1915). The close agreement between the negative radial velocities of M31 and M32 (-300 km/s) confirmed their physical association.

The great distance and extragalactic nature of M31 (and thus M32) was first demonstrated by Lundmark in 1918, by comparison of the apparent magnitudes of novae and brightest non–variable stars in M31 and in the Galaxy (Lundmark 1919).

In the same year Curtis (1918) discovered the nuclear jet in M87 with the 36–inch Crossley reflector of Lick Observatory.

In 1921 Hubble noticed the presence of 21–st magnitude star–like images around M87 on photographs taken with the 100–inch Hooker reflector of Mt. Wilson Observatory (Hubble 1923).[1] In 1922 Balanowski reported the presence of a "new star" (m = 11.5 and 12.2:) on plates of M87 taken at Pulkowo Observatory on February 24 and March 22, 1919, which was still visible at $m \approx 20$ on a plate taken by Hubble in March 1920 (see Hubble 1923).

2. OPTICAL STUDIES FROM 1925 TO 1945

The classification of "non-galactic" nebulae, introduced by Hubble in 1924–25, included in the "elliptical" class regular, symmetric, unresolved and structureless extragalactic objects, subdivided by ellipticity (*i.e.*, shape) from E0 to E7 (Hubble 1926). In the competing classification scheme of "anagalactic" nebulae presented by Lundmark (1927), the "globular, elliptical, elongated, ovate or lenticular" nebulae

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[1] Their interpretation as unresolved images of globular clusters came only three decades later (Baum 1955). Even after the commissioning of the 200–inch reflector, Hubble (1949) was still describing them as "a tenuous atmosphere of supergiant stars".

were subdivided by light "compression" toward the center. Hubble's "ellipticals" fitted among the more concentrated objects.

The first systematic study of the light distribution in elliptical nebulae by photographic photometry was published by Hubble (1930). He used a Koch thermoelectric microphotometer to analyze plates taken in the early 1920's at the Newtonian focus of the Mt. Wilson 100-inch reflector. He found that the luminosity distribution could be represented by a generalized form of Reynolds' formula: $I = I_0/(r+a)^2$, where the fitting parameter was in the range $5''$–$1''$ for 15 nebulae of total magnitudes 8 to 13. Hubble attempted to interpret the observations by a truncated isothermal sphere model, and concluded that elliptical nebulae (i) have no definite edge, the maximum detectable diameter increasing with exposure time (until plate saturation), ii) have all the same standard luminosity profile in normalized units of r/a and I/I_0, and (iii) are relaxed self-gravitating systems in (approximate) statistical equilibrium.[2] Between 1930 and 1934, Stebbins and Whitford made the first photelectric measurements of magnitudes and colors of M32 and other elliptical galaxies with a Potassium hydride cell attached to the Mt. Wilson 100-inch telescope (Stebbins & Whitford 1936, 1937). When the recording microphotometer came into more general use after 1930, tracings of long-exposure photographs at several observatories, including Cambridge, Harvard and Mt. Wilson (see, *e.g.*, Shapley 1934), produced large increases in the maximum detectable diameters of galaxies, especially ellipticals. The first photographic isophotes of NGC 205 were also produced with this instrument by Reynolds (1934), on plates taken with the Helwan Observatory 30-inch reflector.

The first visual, photographic and interferometric high-resolution study of the center of M32 was made in 1934-35 by Sinclair Smith with the Mt. Wilson 100-inch reflector (Smith 1935). From his failure to detect interference fringes in the image of M32 with a makeshift Fizeau-type interferometer with a 55-inch equivalent baseline, he concluded that no star-like central source smaller than $0''08$ could be detected in the nucleus. With the 2.5 m mirror at full aperture and various eyepieces (up to x600) he estimated the semi-stellar nucleus to be $1''1$ in apparent diameter on two nights of good seeing, when the seeing disks of adjacent stars of comparable magnitude were $0''5$, and concluded that the seeing-corrected diameter of the nucleus was $0''8 \pm 0''1$. He also noted that, with the photographic magnitude (13.4) assigned by Hubble to the "nucleus" (that is, the $1'' - 2''$ image recorded by the shortest exposures), its surface brightness was far in excess of the extrapolated I_0 value derived from the Reynolds-Hubble formula. Hence, there was in the center a spike of light in excess of that predicted by a quasi-isothermal model. Finally, he placed an upper limit of 2% on the amount of linearly polarized light detectable photographically, which refuted the light scattering model resurrected by Ten Bruggencate (1930*a*). Smith concluded that M32 is a very dense system of solar-type *dwarf* stars (Humason had classified the spectrum as G3 "with dwarf characteristics").

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[2] In retrospect it is rather surprising that neither Hubble, nor anyone else at the time, commented upon the unexpected applicability to E galaxies of an empirical formula introduced by Reynolds to describe the central regions of a *spiral*. Nearly three decades elapsed before the decomposition of the luminosity profiles of M31 into disk and spheroidal components attracted attention to this remarkable similarity between the gross photometric structures of ellipticals and of the bulges of spirals (de Vaucouleurs 1958*b*, 1959).

An important contribution to the surface photometry of elliptical nebulae was published by Redman, assisted by Shirley (1936, 1938), who used the old Common 36–inch reflector of Cambridge Observatory and a newly developed photoelectric microphotometer built by Carroll and Moss (1931) to measure the luminosity profiles of 15 elliptical galaxies. This study includes the first serious discussion of the multiple sources of systematic and accidental errors in photographic photometry of galaxies and the first determination of the point spread function of the instrument.[3] Redman was especially aware that the parameter I_0 of the Reynolds-Hubble formula could not possibly represent the true peak brightness, and correctly concluded: "It is probable that the determination of the true surface luminosity distribution of any elliptical nebula is beyond the present resources of astronomy."

In 1938 Shapley discovered, on small–scale patrol plates taken at Harvard southern station, the Sculptor and Fornax systems, the first examples of a new type of spheroidal system, akin to elliptical galaxies, but of much lower star density (Shapley 1938*a, b*). Resolution into stars with the 60–inch reflector of the Boyden station, and detection of short–period variables, probably of RR Lyrae type, with the 100–inch reflector at Mt. Wilson by Baade and Hubble soon indicated the order of magnitude of the distance and confirmed the dwarf character.

The last notable pre–World War II paper was a dynamical study of NGC 3115 (then the E7 prototype) and NGC 4494 (E0) by Oort (1940), which included luminosity profiles measured on plates taken at the Newtonian focus of the Mt. Wilson 1.5 m telescope.

In 1944 came the well–known successful resolution of the bulge of M31 and its elliptical satellites into red giant stars by Baade, on photographs taken in red light and under exceptional seeing conditions with the Mt. Wilson 100–inch reflector (Baade 1945).

3. SOME HIGHLIGHTS 1945 TO 1975

3.1 The $r^{1/4}$–Law

In 1946 I began a program of photographic photometry of galaxies, the first phase of which was reported in 1948; it included (*a*) a critical review of earlier works, tracing their poor agreement to a variety of faulty observing, calibrating and recording techniques (de Vaucouleurs 1948*a*); (*b*) a detailed discussion of the main sources of systematic and accidental errors in galaxy photometry (de Vaucouleurs 1948*b*), and (*c*) a study of the central regions of two ellipticals (NGC 3379, 4649), one "E7" (NGC 3115) and one bulge–dominated edge–on spiral (NGC 4594), on plates taken at the Cassegrain focus of the 80–cm reflector. The PSF measured out to $20''$ had a Gaussian core of dispersion $\sigma = 1''25$. Although the exposures were short (5–60 min.) and only a limited range of intensities could be measured, about 3 dex (7–8 mag), it was sufficient to discover that the luminosity profiles of the spheroids could be well fitted with a very simple formula of the form $\log I = A - B^{1/4}$ (de Vaucouleurs 1948*c, d*).[4] Although it has no free fitting parameter,

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[3] Unfortunately, as I showed later (de Vaucouleurs 1958*b*), their calibration had a large scale error.

[4] This formula was soon found to apply equally well to the distribution of galaxies in rich, Coma-type clusters (de Vaucouleurs 1948*e*) and, later, to the

this formula fitted the average of Hubble's observations extremely well and, over a range in excess of 4 dex ($> 10\,mag$), the average of the (then) five best observed ellipticals (de Vaucouleurs 1953). Because, unlike the Reynolds–Hubble formula, its surface integral converges, it leads to a rational definition of the total (asymptotic) luminosity, and of effective scale factors (I_e, r_e) which have been widely used in many studies.[5]

The space density distribution in a spherical system obeying the $r^{1/4}$–law in projection was first derived by Poveda, Iturriaga & Orozco (1960), and more precisely by Young (1976) for the range of normalized distances $10^{-6} \leq s = r/r_e \leq 260$ (from the centers of the densest systems, such as M32, to the outermost fringes outside clusters).[6]

3.2 New or Peculiar Types of Elliptical Galaxies

Between 1948 and 1953 the first radio galaxies were discovered and identified with peculiar E galaxies, beginning with Cen A and Vir A located by means of the "sea interferometer," near Sydney, and soon identified with NGC 5128 and 4486 by Bolton, Stanley & Slee (1948, 1949) and confirmed by Mills (1952*a*, *b*, 1953). Then the radio source For A, detected by Stanley and Slee (1950), was identified with NGC 1316 by Shklovskii & Kholopov (1952) and, independently, by Mills and de Vaucouleurs (1953, 1954).

About 1950 Zwicky discovered the first small, high–surface brightness "compact" elliptical galaxies, with apparently sharp boundaries, the prototype of which is NGC 4486 B, near M87 (Zwicky 1963, 1971)

In 1956 another type of low–luminosity elliptical galaxy, having a semi–stellar nucleus, was discovered by Reaves on plates of the Virgo cluster taken with the Lick 20-inch astrograph (Reaves 1956, 1962).

A new type of supergiant elliptical galaxy, distinguished by an extended envelope (and occasionally multiple cores, as in NGC 6166), was identified by Mathews, Morgan & Schmidt (1964). These objects (labeled cD by Morgan) are often near the centers of rich clusters, but some have been found in groups and poor clusters.[7]

3.3 Truncated Isothermal Models and the King Formula

Hubble's attempt to fit the observed luminosity distribution by a density truncated

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distribution of luminosity in the bulges of early–type spirals, such as M31 (de Vaucouleurs 1958*b*, 1974*b*) and of globular clusters in galaxies (de Vaucouleurs 1977, 1978). Recent computer simulations show that this distribution easily results from the gravitational collapse of a system of collisionless particles under a broad range of initial conditions and assumptions (Binney 1982; van Albada 1982).

[5] Note that the definition of effective parameters requires only that the total luminosity be finite; it is not restricted to E galaxies.

[6] It has been objected that the $r^{1/4}$ law is unsatisfactory, because it leads to a diverging central density at $r = 0$. This is akin to objecting to the law of perfect gases, $pV/T = k$, on the grounds that it implies that $p \to \infty$ when $V \to 0$.

[7] An extensive elliptical envelope or "corona" had already been detected on long–exposure photographs and photoelectric scans of NGC 5128 made at Mt. Stromlo Observatory in the 1950's (de Vaucouleurs & Sheridan 1957).

isothermal sphere was purely ad hoc and had little theoretical basis. A first attempt to provide a self–consistent theoretical model was made by Belzer, Gamow & Keller (1951). Between 1953 and 1956 Woolley and collaborators at Mt. Stromlo developed detailed analytical models of velocity truncated isothermal distributions with a mass function which could reproduce the $r^{1/4}$–law reasonably well (Woolley 1954; Woolley & Robertson 1956). This type of model was developed further in the 1960's by Michie (1963), Fish (1964) and King (1966*a*, *b*), who also introduced a widely used semi–empirical fitting function (King 1962):

$$(f/k)^{\frac{1}{2}} = \left[1 + (r/r_c)^2\right]^{-\frac{1}{2}} - \left[1 + (r_t/r_c)^2\right]^{-\frac{1}{2}},$$

where r_c is the "core" radius, and r_t is the "tidal" radius. This formula gives a very good representation of star counts in tidally–limited globular clusters and low–density spheroidal galaxies of the Sculptor and Fornax types (Hodge 1961*a*, *b*; 1962; de Vaucouleurs & Ables 1968; Hodge and Michie 1969). It does not fit normal E galaxies well (assuming $f/k \approx I/I_0$), particularly the central spike, and the "tidal radius" r_t often reflects more the detection threshold of the photometry than any physical boundary to the galaxy, as illustrated by the table.

Underlying all these models was the concept of statistical equilibrium by two–body relaxation, on a time scale much longer than the Hubble time. The way out of this difficulty came when Lynden–Bell (1967) introduced the concept of fast relaxation during an early collapse phase of galaxy formation and when Wolfe and Burbidge (1970) suggested the possible presence of massive black holes in the centers of E galaxies to account for the central spike.[8]

3.4 Apparent Ellipticities and True Shapes

Until recently, all attempts to find the apparent ellipticity of the two–dimensional image (the "nebula") on the sky, and the three–dimensional shape of the object (the "galaxy") in space, have been statistical in nature, and depended on the long–unquestioned assumption that the isophotal surfaces are homothetic oblate spheroids with axes $a = b > c$. As early as 1926, Hubble had attempted to determine the frequency function of the true axis ratio c/a from the relative frequencies of apparent axis ratios of 85 nebulae of types E0–E7. He concluded that the distribution of c/a is nearly uniform from 0.3 to 1.0.

Hubble's data were reanalyzed by Ten Bruggencate (1930*a*, *b*) who curiously concluded that the true shape of all ellipticals is actually E7! This conclusion was criticized by Machiels (1930*a*) who confirmed Hubble's results. Further discussion by Machiels (1930*b*, 1933) of the axis ratios among the objects classified E in the Shapley–Ames (1930) survey of the Virgo cluster, and in their (1932) survey of the brighter galaxies, reconfirmed Hubble's conclusions.

In 1950 a reanalysis of the more than 200 E objects in the Shapley–Ames catalogue led Wyatt (1950) to a different view: he found a significant excess of

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[8] Numerous computer simulations have since confirmed that density distributions closely approximating the $r^{1/4}$ distribution can be obtained through the collapse of collisionless systems under a wide range of initial conditions and assumptions, but it is still moot whether a massive black hole is the correct interpretation for the central spike.

A Short History of the "Tidal Radius" of NGC 3379

Source of Photometry	Range $r <$	Threshold μ_B	Source of r_t	r_t
Dennison (1954)	3′4	25.3	King (1962)	5′
Miller and Prendergast (1962)	4.4	27.4	King (1966*a*)	7′8
de Vaucouleurs and Capaccioli (1979)	$> 16'$	> 30.9	deV.&C.(1979)	20′
Kormendy (1977)	No tidal truncation, but "tidal extension"			

highly flattened systems over nearly spherical ones, and a definite deficiency of systems of intermediate flattening (E3).[9]

These early discussions were confused by inclusion of lenticular galaxies and poorly-resolved S0/a and Sa spirals (E: objects in S-A catalogue).

Fresh material on 48 E, E^+ objects in the Survey of Southern Galaxies with the Mt. Stromlo 30-inch Reynolds reflector (de Vaucouleurs 1956), and using both estimated type and measured axis ratio, led again to agreement with a uniform distribution of true ellipticities, but the sample was too small for definite conclusions.

The (First) "Reference Catalogue" (de Vaucouleurs & de Vaucouleurs 1964, RC1) provided a much larger, more homogeneous all-sky sample which was first anlyzed by Sandage, Freeman & Stokes (1970), and by several others later. The "Second Reference Catalogue" (de Vaucouleurs, de Vaucouleurs & Corwin, 1976, RC2) provided still better and richer material, which was first analyzed by de Vaucouleurs & Pence (1973), and later by Binney and de Vaucouleurs (1981). All these studies indicated that, if E galaxies are homocentric oblate spheroids, the most frequent true ellipticity is E3–E4, and spherical and highly flattened systems are rare.[10] The problem is complicated by the fact that the apparent ellipticity of the isophotes depends on the brightness level, as was noted by Redman and Shirley (1938) who, from their study of 15 ellipticals concluded that "isophotal contours do not always have a constant ratio of minor to major axis...There is no uniform

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[9] That is precisely the opposite of what is indicated by modern studies; see e.g., de Vaucouleurs (1974*a*); Binney & de Vaucouleurs (1981).

[10] More recently, it was realized that statistical studies of the ellipticity distribution alone cannot unequivocally define the true shapes of E galaxies, whether oblate, prolate or triaxial, and that photometric and kinematic information is needed to solve the problem.

tendency in the changes of shape of the contours, either to become more circular with diminishing surface brightness, or vice versa."

Two decades later these conclusions were generally confirmed by Hazen (1960), in her study of 15 Virgo cluster ellipticals with the Williams and Hiltner isophotometer, except that in this sample the ellipticity was generally increasing with radius up to a maximum reached near the effective radius, followed by a decrease in the outer parts. Two more decades elapsed before the trend of ellipticity with radius became again, during the past ten years, an active subject of investigation, together with the phenomenon of "isophote twists" or rotation of the major axes, first reported for the central parts of IC 1459, type E3–4, and, possibly NGC 1549, type E0, by Evans (1951),[11] and first measured by Hazen in 1957 on equidensity tracings of two E2 Virgo cluster ellipticals (NGC 4459 and 4472).

3.5 Integrated Colors and Color Distribution

The first two–color photoelectric photometry of galaxies by Stebbins & Whitford, using the Mt. Wilson telescopes, published in 1937, included 30 "ellipticals" (some recognized today as lenticulars). It showed them to be redder then spirals and slightly redder than suggested by their G or G–K spectral classification by Humason. This was confirmed by their work with a longer baseline (Stebbins and Whitford 1952).

Pettit (1954) reported, from two–color photometry of 58 ellipticals measured through two or more field apertures with the Mt. Wilson reflectors, that 52% are redder near the center, 32% bluer and 16% unchanged.[12]

Integrated magnitudes and colors of 20 ellipticals (including Local Group dwarf systems) measured by photographic surface photometry were included in the catalogue of Holmberg (1959).

The first *multi*–color photometry of M32 by Stebbins and Whitford (1948) showed significant departures from stellar spectra of matching P–V color. This effect is a consequence of the compositeness of the stellar population.

In 1957–58 I began a long–term program of photoelectric photometry of galaxies in the UBV system, initially with the 20– and 42–inch reflectors at Lowell Observatory (continued at McDonald Observatory with the 36– and 82–inch reflectors since 1960). The first results included 15 ellipticals (de Vaucouleurs 1958*a*). Simultaneously, Tifft (1961, 1963) was securing four–color photometry with the 60–inch Mt. Wilson reflector. The two studies were combined, together with earlier two–color data, in the first general catalogue of galaxy colors in the UBV system (de Vaucouleurs 1963), including 21 ellipticals. This study demonstrated clearly the presence of a color gradient (redder near center) in normal E galaxies and gave the first application to distance determinations of the color–luminosity relation reported by Baum (1959, 1961).

In 1966 Wood published 12–color photometry of galaxies with applications to population analysis, but Martin & Bingham (1970) soon demonstrated—by prin-

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[11] The most clear cut example, NGC 1291, since reclassified as a barred S0/a, is no longer relevant.

[12] However, in a rediscussion of Pettit's data restricted to the larger and brighter objects ($m_{pg} \leq 13.0$), I found that actually all are redder near the center by 0.1–0.2 mag, and that the mean color index, $< P - V >= 0.87$, is slightly redder than the mean (0.85) for lenticulars (de Vaucouleurs 1959).

cipal component analysis—that only *three* independent parameters (of which two are dominant) can be defined by multicolor photometry.

3.6 Masses, Luminosities and Velocity Dispersion

The first estimate of the mass of M32, $M \approx 2.5.10^{10} M_\odot$ for an assumed distance of 0.5 Mpc), was made by Martin Schwarzschild (1954), from an asymmetry in the shape and rotation curve of M32 tentatively attributed to dynamical interaction.

The first formulation of the virial theorem for a spherical galaxy having a constant M/L ratio, and a projected luminosity distribution given by the $r^{1/4}$ law, was given by Poveda (1958) and Poveda, Iturriaga & Orozco (1960): $M_T = 3r_e\sigma_v^2/G$, where r_e = effective radius (in projection), σ_v = central velocity dispersion (in space). The first estimates of the virial mass of M32 using this formula was made by Burbidge, Burbidge & Fish (1961). The masses of other ellipticals were calculated by Poveda (1961), using velocity dispersions measured mainly by Minkowski (1961). This was soon followed by the first systematic discussion of masses and mass/luminosity ratios of E galaxies by Fish (1964).

Three–component (core, bulge, halo) dynamical models of E galaxies were first discussed by Einasto (1972, see also de Vaucouleurs 1974*a*). In these models the halo component, having a low M/L ratio (≈ 3), was supposed to be the only one present in low–density dwarf systems of the Scl, For type, with the bulge and core populations increasingly important in galaxies more massive than 10^9 $M_\odot$.

The first hint of "a possible luminosity effect in the spectra of K–systems" was discovered by Morgan & Mayall (1957), who noticed that absorption lines looked more diffuse in giant systems and suggested that "a line width–absolute magnitude relationship ... may be used for the determination of spectroscopic parallaxes of more distant galaxies".

This possibility was examined by Minkowski (1961) who produced the first plot of velocity dispersion (on a linear scale) versus absolute photographic magnitude for 14 galaxies. The large scatter in the diagram led him to conclude that "the velocity dispersion does not seem to be a good criterion for absolute magnitude," but neither his estimates of σ_v, based on an ingenious, but imprecise analog photographic technique (the unsharp slit), nor the relative distances of the test galaxies, were good enough for definite conclusions.

Although the first quantitative measurements of σ_v in M32 by detailed photographic spectrophotometry and numerical convolution of template star profiles had already been made by Burbidge, Burbidge & Fish (1961), it was not until the early 1970's that new and more reliable methods of measurement by digital television or photoelectric techniques were introduced by Morton & Chevalier (1972, 1973), and at McDonald Observatory (mainly unpublished). But as late as 1973 values of σ_v had been obtained for less than a dozen galaxies, of which five only were ellipticals (NGC 221, 3379, 4486, 4486B, 4494), and agreement between independent estimates was poor (de Vaucouleurs 1974*a*).

3.7 Dawn of a New Era: 1975–76

The traditional concept of elliptical galaxies as oblate spheroids flattened by rotation about the polar axis was still dominant 11 years ago (Larson 1975; Gott 1975; Wilson 1975) when Bertola & Capaccioli (1975) reported their observation that the E5 galaxy NGC 4697 is a slow rotator with a maximum rotation velocity of

$V_r \leq 65\,km\,s^{-1}$. As Binney (1976) was quick to point out, comparison of this value with the velocity dispersion ($\sigma_v = 310\,km\,s^{-1}$) measured by Minkowski, implied that there is not enough kinetic energy in the rotation to account for the observed ellipticity if the galaxy is an oblate spheroid.[13]

In the same year the reality of the correlation between σ_v and absolute magnitude for elliptical galaxies was finally demonstrated by Faber & Jackson (1976). The slope of the $M - \log \sigma_v$ relation was consistent with a simple dynamical model implying $L/\sigma_v = $ const. Soon afterward, Kormendy (1977) discovered a correlation between the effective parameters (radius and surface brightness, r_e and μ_e) of the $r^{1/4}$-law for a sample of 17 E galaxies (measured mainly by King).

These new discoveries opened a new era in elliptical galaxy research which has developed explosively ever since with the entry into the field of many new workers, the growing application of new detectors and the use of ever more powerful methods of digital data processing which make the pre–1975 era look almost like the age of the horse–and–buggy. It is the subject of this conference to review these more recent developments.

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[13] Ironically, with revised values of σ_v and V_r, today NGC 4697 is regarded as one of the faster rotating ellipticals in terms of the reduced velocity ratio V_r/σ_v.

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DISCUSSION

Rood: A few years ago, Walter Jaffe published a fitting–formula in the *Monthly Notices* (1982, **202**, 995), to describe the luminosity distribution of elliptical galaxies. Jaffe's formula has the same number of fitting parameters as the $r^{1/4}$–formula and implies a stellar distribution function which lends itself nicely to theoretical studies. How well does the Jaffe formula fit the observational data relative to the goodness–of–fit of the $r^{1/4}$–formula?

Jaffe: My suggested form for the light distribution in ellipticals fits all the data for NGC 3379 as well as the $r^{1/4}$ law, and is analytically much more tractable.

de Vaucouleurs: I regret to admit that I was not familiar with your paper, but after checking it seems to be an excellent single formula for the *space* density which projects into a good fit of the observed $I(r)$ of NGC 3379. The analytical expression for the *projection* is tractable but not simple; the $r^{1/4}$ law is simple in projection, but not tractable in space. Your formula implies more mass (light) in the faintest outer parts.

Djorgovski: The $r^{1/4}$ law has no shape parameters. This would imply that *all* surface brightness profiles have the same shape on log–log plots. It is a well–documented fact that they do not: there is a variety of shapes.
Second, I have fitted the $r^{1/4}$ laws to my surface photometry profiles, outside 3 arc sec, in order to avoid seeing effects. The $r^{1/4}$–law is a fair approximation in many cases, but there are highly significant deviations in many cases as well, and there are no evident systematics in these deviations.

de Vaucouleurs: I agree. However, I consider it a *good* feature of the $r^{1/4}$ law that it has no 'fudge' factor. The remarkable fact is that it does fit so well so many systems from E galaxies, to the globular cluster systems of our Galaxy and M31, to the distribution of galaxies in clusters like Coma. This remains as a challenge to theorists.

Lauer: I have compared my observed high–resolution CCD surface photometry to de Vaucouleurs models that are fitted to the envelopes and convolved with the observed point spread function. In no case in my 42 galaxies observed does the de Vaucouleurs law fit the apparent cores. For well resolved galaxies it predicts too much light in the center. For poorly resolved galaxies it predicts too little light.

de Vaucouleurs: I will look at your welcome new data carefully. My impression is that the higher the density of the system the better the fit to the $r^{1/4}$ formula, and the lower the density, the poorer. Of course, the formula was never claimed to fit globular clusters, or low density spheroidals, which are very well fit by the King formula. As you know, I have documented in detail real departures from the $r^{1/4}$ (*e.g.*, excess in the center of N3379, deficiency in M87 outside the central nonthermal source). As Steve Strom remarked once, the $r^{1/4}$ law is a good 'French curve' against which the departures of real galaxies can be studied. Again all the new CCD work is very welcome!

King: I regret that pressure of time has kept you from discussing the techniques to which you have contributed so much. Regarding sky level, you showed how sensitive the outer photometry is to a correct sky determination. You also showed one limit of $\mu = 30.9$. Can you give us precepts for determining a good sky value?

de Vaucouleurs: The 30.9 is a normal value which has a calculated mean error of -1 mag on the bright side and $+\infty$ on the other as shown by the error bar on our Fig. 2 in *Astroph. J. Suppl.*, **40**, 704, (1979). We attach no real significance to it. As we showed in *Astroph. J. Suppl.*, **52**, 465, (1983), real measurements with a m.e.$<$ 0.1 mag can be pushed down to $\mu_B \approx 28\,B/ss$. Below this level—although readings can be secured—their significance is lost in the irreducible cosmic noise (irrespective of detector) due to galactic cirri, fluctuations due to subthreshold stars and galaxies etc. We have discussed these sources of error at length in *Ann. d' Astrophys.*, **11**, 247, (1948) and *Astrophys. J. Suppl.*, (1983), *op. cit.*

Bertola and Kormendy.