Chapter 1
Bulges: Seen from a Philosophically-Informed Historical Perspective

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Abstract Most every graduate student in astronomy today knows what the "bulge" of a spiral galaxy is by name and what it looks like. A century ago few professional astronomers knew, or even cared. We trace the early and quite casual usage of the term (and its competitors) and then follow the later and gradually more strict adoption of the term "bulge", needed to call out a major component of galaxy morphology. In the specific context of the Milky Way "The Galactic Bulge" was a proper name. Only later, as they were seen and measured in other galaxies, were these same structural features to become known generically as "bulges". That term finally won out over its more unwieldy competitors such as the "amorphous central region", the "unresolved nuclear region" or the highly ambiguous term "central nucleus".

1.1 Introduction

A bulge. The very word brings to mind a three-dimensional object, implicitly in juxtaposition with some other spatially co-existing object or component that is itself comparatively flat(ter). Taking a two-dimensional projection (i.e., an image) of a galaxy and declaring it to contain a 3D bulge assumes a great deal of prior (passed down, taught and learned) knowledge about galaxies in general, including their components and the intuited relative disposition of those parts in space and time. With further study the stellar make-up of bulges becomes known, the age distributions and chemical composition distributions of those same stars are teased out, and the gross kinematics of selected examples get studied. Slowly the flattened image, still frozen in time, starts to thaw, to become a dynamic, evolving entity, deprojected, inverted and modeled in our collective minds' eye and in our computers over the simulated course of the age of the Universe. A bulge.

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E. Laurikainen et al. (eds.), *Galactic Bulges*, Astrophysics and Space Science Library 418, DOI 10.1007/978-3-319-19378-6_1

The same process of understanding might be argued for any and all of the morphological components currently cataloged and studied in galaxies whether they are seen locally, or at the limiting resolution of our best space-based telescopes, looking out to the highest recorded redshifts and earliest times in the assembly of "galaxies", at those distant and formative epochs. But bulges hold a special place in the history of our recent realization and gradual acceptance of galaxies as truly major constituents of the universe. It might be argued by some that the bulge of our own Milky Way has, since the dawn of humans on this planet, been visible to all who cared to look at the sky on a moonless night (Fig. 1.1). But it is only with highly informed hindsight that the bulge of our galaxy is in any way obviously akin to the prototypical bulges seen in "extragalactic" nebulae.

Fig. 1.1 The bulge of our Milky Way galaxy passing high above the dome of the 2.5 m duPont telescope at Las Campanas, Chile, as photographed by the author in August 2014. Compare this with the image of the edge-on galaxy NGC 0891 in Fig. 1.2 (below)

1.2 A Bulge by Any Other Name …

So where did the concept of a bulge come from, and when did the word *bulge* enter our astronomical vocabulary? The answer is not easy to come by. The transition was neither abrupt nor particularly well orchestrated. It just grew.

From surveying in the literature one thing is for clear: none of the luminaries of the time who were studying galaxies in the 1950s or 1960s were using the term "bulge" consistently. Sometimes it was used figuratively and descriptively; sometimes it was used dramatically and for effect. And then too it was often simply inserted almost incidentally.

The term "bulge" appears to have come into commonly accepted astronomical usage by way of two, parallel and somewhat disjoint applications of the word: one in the specific context of the Milky Way and the other in the more general context of the "anagalactic" nebulae. But independently of making the identification of our galaxy and its "bulge" with external galaxies and their "bulges", something else was in play. As we shall see below, in many cases there were colorful attempts to describe features in galaxies without coming out and explicitly naming them. And so the physical objects we now call "bulges" were often (even in the same sentence) referred to as an "amorphous feature", "a central condensation", "a lens-like feature" or "bulge-like". This colorfully flowing prose kept the readers attention but it never categorically graced the feature with a name. The honor of a name seems to have been first and most naturally bestowed upon the central region of the Milky Way. In the galactic context, numerous authors, almost simultaneously, began talking about "the Galactic bulge" as a named feature. And that name stuck sooner and more robustly than using the word "bulge" did for the same structures seen in the nearest galaxies already imaged at that same time. So, we have two parallel stories: one about the description of the Milky Way and the early adoption of the proper name, "the Galactic Bulge", and the other about the nature of galaxies in general and the earliest attempts to describe, without actually naming or self-consistently referring to various features, most notably the central features that we today call "bulges". Walter Baade undoubtedly played a critical role in both of these stories.

In his overview of "The Nebulae", Heber Curtis (1933) makes the distinction between the "Nuclear Portion" of "true spirals" and an outer region which is home to "whorls". In a section entitled "Conspectus of Forms Assumed" Curtis goes on to say that the whorls can come in various flavors, including "Delicate", "Rather compact", "Moderately open", "Two-branched", "Single"; while the "Nuclear Portion" is described as being "Rather large", "Small and bright", "Tri-nuclear", "Quite faint" or "Not apparent". While the term "bulge" has not yet appeared on the scene, it is amusing to note that few of Curtis's other terms and descriptors survived the transition either: *whorls!*

The explicit use of the word "bulge" began turning up by mid-century. Hubble (1943), in a not-often-cited paper, concerning the direction of rotation in spiral nebulae, talks about "dark material scattered through the central *bulge* of a tilted nebula" and repeatedly uses the phrase "central bulge" through the paper, only to disappoint us, once again, by stating that "half of the central *lens* is blotted out ..." One can only conclude that in his mind "bulge" and "lens" were synonymous. Five years later, this time back in the galactic context, Stebbins and Whitford (1948) reported making a 2μ "sweep across the galactic equator" showing "a *bulge*, agreeing closely in position and form with that previously found a year earlier (Stebbins and Whitford 1947). In this latter paper, they off-handedly attribute Baade with having shown that "the great cloud in Sagittarius ... is undoubtedly the outer region of the *bulge* about the galactic center." Curiously, at about this same time, it was still possible for the AAS (American Astronomical Society) in 1959 to accept a contributed talk entitled "The Visual Milky Way" wherein Sergei Gaposchkin (1959) described "the visual panorama of the whole Milky Way done with *pen and India ink,* drawn during my stay in Australia". He goes on to say that "around Ophiuchus, Sagittarius, and Scorpius there is a definite halo or *bulge*." (emphasis mine throughout). By way of contrast, Fig. 1.1 is a 20 s exposure of the Galactic Bulge using a standard 35 mm camera; no pen and ink required.

We now transition to Baade's charming introduction to the classification of galaxies as found in his 1958 Harvard Lectures as captured and edited by Cecilia Payne-Gaposchkin and published in the book entitled "Evolution of Stars and Galaxies" (Baade 1975). In the opening chapter, "Classification of Galaxies" Baade is quoted as saying:

"In classifying the spirals, Hubble distinguished the groups Sa, Sb and Sc, the distinguishing criteria being essentially the spiral arms. For instance in his description of Sa the spiral arms emerge at the edge of *the central system*; in the earlier spirals both they and the *central lens* are still unresolved, and the arms are densely coiled. As we proceed along the series, the *central nuclear area* shrinks at the expense of the growth of the arms, which by and by uncoil, until finally the *central area* has shrunk to a *semi-stellar point*, and all the mass seems to be in the spiral arms. This is Hubble's original description, but he agreed completely that it would be simpler today to classify the spirals simply by the size of the *central lens*. This with *very large central lenses* can be called Sa; and those with *intermediate central lenses*, Sb; and those where the *lens* has shrunk to a *semi-stellar point* (actually a huge cluster of stars), Sc. In what follows I shall adopt this very simplified system, based on the size of the *central lens*." There can be little doubt that when Baade was using the term "lens" he was referring to what we would today call the "bulge".

The key practitioners in the early days of galaxy classification played pretty fast and loose with their terminology, especially when it came to describing the major features that went into these classification systems. Perhaps they felt that the classification scheme was intrinsically qualitative and so that the terms used could be metaphorical and/or illustrative rather than rigorously defined or even consistently applied. However, science is not poetry, and eventually people need a common language if they are going to build a coherent ontology and then quantify, study and discuss the same unambiguously identifiable features in physical systems. The quantification of galaxy properties more that likely force the nomenclature to become a bit more rigorous.

1.3 Quantification and the Bulge-to-Disc Ratio

de Vaucouleurs (1959a,b) was among the first astronomers to bring quantitative methods to galaxy classification. And he speculated that "It is conceivable that a precise classification along the spiral sequence could be made to depend on the ratio between the integrated luminosities of the *spherical* and *flat* components; i.e., on the fraction of the total luminosity contributed by the central bulge producing the excess of light above the exponential component". And earlier he categorically states "Sub-types, noted Sa, Sb, Sc, are defined by the relative size of the *nucleus* and the degree of resolution and opening of the spiral structure."

However, Sandage (1961), in an implicit but focused rebuttal, is quick to point out "For many years it was thought that the third classification criterion of the relative size of *the unresolved nuclear region* usually agreed with the criterion of the arms. Inspection of large numbers of photographs shows that, although there is general correlation of the criteria, there are Sa galaxies that have *small nuclear regions.* This does not mean that Sa galaxies do not exist with large amorphous central regions devoid of dust and spiral structure we only wish to point out that a large amorphous central region is not a prerequisite for Sa galaxies."

Sandage (1961) in his self-effacing publication, illustrating and annotating Hubble's (posthumous) classification of galaxies, hardly every is the word "bulge" explicitly used when discussing the classic spiral galaxy Hubble Sequence: Sa, Sb and Sc. Indeed, Sandage does repeatedly talk of "unresolved nuclear regions", or "the large amorphous center" of NGC 3898, "the amorphous central region" of NGC 4579, "the completely amorphous central *nucleus*!" (emphasis and italics mine) for NGC 2775, and finally "the peculiar square-shaped nuclear region" of NGC 7332 and the "peculiar 'box-shaped' nucleus" of NGC 128. "Nucleus", "Nuclear Region", "Center", "Central Region" and "Central Nucleus" all dance around what we would now simply call the "Bulge".

A few years later, in an attempt to meld the two worlds (galactic and extra-galactic), and put our Milky Way galaxy into Hubble sequence, Halton Arp (1965) became the first author to explicitly put into print the term "bulge-to-disc ratio" when he said "Probably the *bulge-to-disc ratio* is the physically most important criterion…" in classifying our Milky Way galaxy … "because it is a measure of the proportion of low angular momentum to high angular momentum populations."

At long last the loop had been closed: our Galactic Bulge joined the ranks of extragalactic bulges, and the bulge-to-disc ratio became one of the first *quantitative* measures of galaxy type (Fig. 1.2).

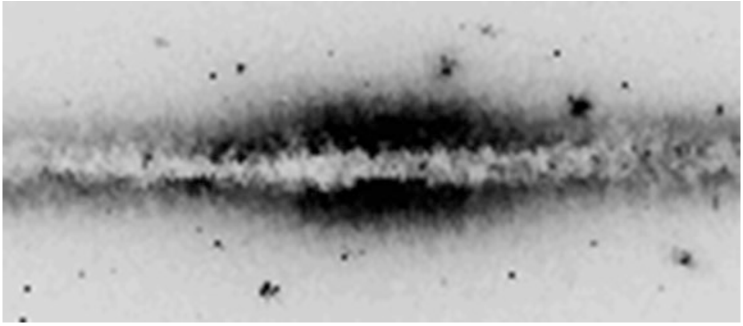

Fig. 1.2 An optical image of the edge-on galaxy NGC 0891. Notice the similarity of this image to that of the bulge of our Milky Way galaxy shown in Fig. 1.1. This and other similar images of other galaxies with dust lanes projected on their "central amorphous regions" must have played an important role in making the case that the Milky Way was just one of many such "Island Universe" galaxies

1.4 CCD Detectors and Large Samples

With the introduction of linear CCD detectors in the mid-1980s the ability to acquire calibrated data on significant samples of galaxies allowed observers to decompose the globally most obvious inner and outer features of galaxies, now regularly referred to (qualitatively at least) as discs and bulges. Using CCDs Steve Kent (1985) measured both components and published "bulge/disc" decompositions for over 100 galaxies of all morphological types. Caught at a time of transition between photographic plates and CCD detectors Dave Burstein (1979) published photographic photometry of 18 S0 galaxies and derived "disc-to-bulge" ratios for 12 of them. This followed close on heels of another photographic "decomposition" study of S0 galaxies undertaken by Kormendy (1977). In this paper Kormendy made a last stand against the use of the word "bulge" and subtitled his Paper III: "Decomposition of Observed Profiles into Spheroid and Disc Components."

Here, perhaps, was a missed opportunity. Most of the quantitative evidence (as gleaned from the fact that the $R^{1/4}$ Law fit the radial light profiles of both bulges and elliptical galaxies) suggested to many that the two systems had much more in common. Perhaps ellipticals were simply discless galaxies, and/or spirals were ellipticals that acquired discs, or even that ellipticals were star piles made from the destruction of many earlier discs. However, as noted in the Introduction, a bulge exists conceptually by virtue of its comparative status with respect to something that it is "bulging out of". Under these circumstances it is cognitively dissonant to even try talking about a bulge without implicitly visualizing a disc (or at least some other additional component). However, if we were to rewind history and declare that the Milky Way and all other spiral galaxies had centrally-located "elliptical components" then the concept of an "elliptical-to-disc ratio" would have unified and simultaneously quantified the entire Hubble classification sequence (not just the spirals) without any discontinuity, be it linguistic, cognitive or numeric. Kent (1985) came dangerously close when he said "The difficulty of distinguishing between elliptical and S0 galaxies in some cases is emphasized." Thinking of galaxies as being morphologically bimodal (ellipticals versus spirals) produces a very different mindset, as compared to the suggestion that all galaxies are part of a continuum, which to first order is described by an "elliptical-to-disc" ratio. Science is, by design, self-correcting, so the truth will win out, but it is interesting to speculate about the rate of convergence had certain words and suggestive phrases been adopted earlier instead of others.

1.5 Early Unification

In a particularly lucid discussion of the terminological chaos left us by Baade, Hubble and Sandage in their descriptions of the inner reaches of spiral galaxies the Russian astronomer B.A. Vorontsov-Velyaminov (1987) wrote the following (slightly abridged version here):

> As we have seen, Hubble adopted the term "nucleus" without any reservation. Even today authors use the word "nucleus" with no explicit statement of just what is meant; as a result misunderstanding often arises, because different kinds of structures, sometimes quite complicated, may be present near the center of a galaxy. We should therefore recommend the following nomenclature.
>
> The central formation, generally an amorphous structure standing out in brightness, with a fairly sharp brightness gradient at its edge and containing no spiral arms, will be called the *nuclear region*. We discriminate nuclear regions of several types.
>
> *Bulge*: A large, nearly globular condensation of light, shaped like an elliptical galaxy. The nuclear regions of type S0 galaxies have this appearance, while type N radio galaxies form a bulge embedded in a rather narrow halo.
>
> *Lens*: A strongly flattened bulge, in a sense. Bright spiral arms emerge from its periphery. If viewed edgewise, a lens is readily distinguished from a bulge, and looks just like a thick lens in profile. Sa and Sb galaxies usually have a nuclear region of this kind.
>
> *Nuclear Disc*: A very thin lens structure, with its thickness small compared to its diameter, even at the center. Bright spiral arms emerge at its periphery. When seen face-on, a nuclear disc is nearly uniform in brightness, and in this respect differs from a lens.
>
> *Nucleus*: A pronounced, nearly globular condensation, resembling a bulge, but smaller in size and luminosity compared to the whole galaxy.
>
> *Core*: A tiny nucleus, of star-like appearance or almost so. A lens may have a nucleus inside, while a nucleus may in turn contain a core.

Even this admirable attempt to clarify the terminology stumbles a bit when it uses the (optician's term) "lens" to describe the astrophysical "lens" (seen edge-on), and too when the "lens" is described as a "flattened bulge" (in a sense!), leaving one wondering which type of lens is being referred to when a "nuclear disc" is described as "a very thin lens structure" (optical or astrophysical?). And finally we come full circle when we are told that a "nucleus" is simply a "small bulge".

At this point the reader is recommended to consult two chapters in this volume: The vastly superior and thoroughly up-to-date discussion of the properties of bulges given by Fisher & Drory in "An Observational Guide to Identifying Pseudobulges and Classical Bulges in Disc Galaxies", and the chapter by Laurikainen & Salo entitled "Observed Properties of Boxy/Peanut Bulges" where we are introduced to higher-order structures making up the inner regions of galaxies, including X-shaped morphologies, vertically thick boxy/peanut bulges, and bar/lens bulges.

A final word on extensions to the concept of a bulge. As linear detectors have become more sensitive and surveys using them have become more widespread there will inevitably be new features found that are either at the subtle edge of detectability within known objects or at the other extreme of being so rare that ever larger samples are required to discover just one of them. "Pseudo-bulges" fall in the former category . . . perhaps. The interested reader is referred to the *Annual Reviews* article by Kormendy and Kennicutt (2004) and the chapter by Kormendy in this volume. In the former, the authors discuss the case of M33 , one of the brightest and well studied galaxies in the northern sky. They note that M33 has a "subtle upturn in surface brightness" and go on to pose the question "Does M33 contain a pseudo-bulge?" Without giving away their answer I will instead refer the reader to the image of M33 found in Fig. 1.3. This picture was originally published by Walker (1964) solidly in

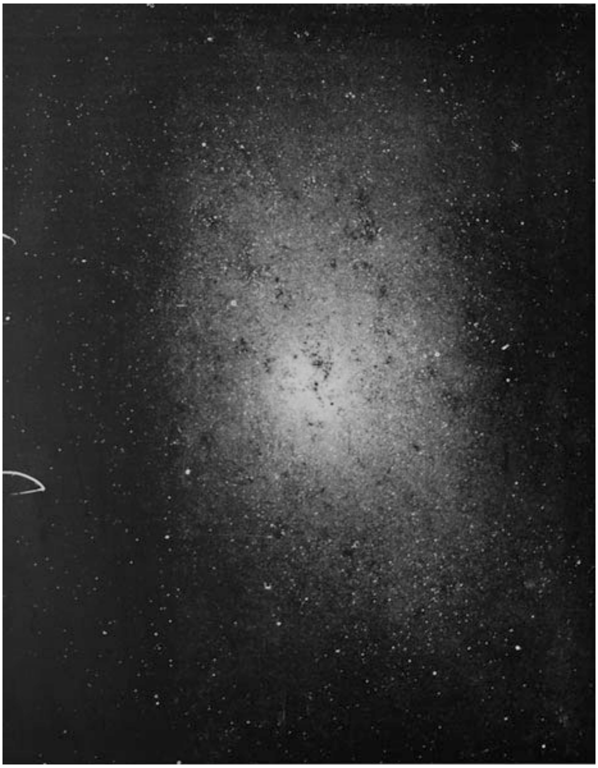

Fig. 1.3 A *color composite* image of M33 (Walker 1964) showing resolved Population I (*blue*) stars in *black* and the unresolved Population II (*red*) stars in *white*

the photographic era, and well before CCDs and linear detectors. What is shown is the result of a photographic combination of images taken in two different (red and blue) bandpasses, differenced and printed to enhance stars and stellar populations of one color extreme or another. They called the technique “composite photography”. It gained little traction and has been largely forgotten. Without further comment I will leave it to the reader to decide whether they see a pseudo-bulge in M33 or not, but here is what Walker himself very cautiously claimed. “The fact that the outline of the system of Population II red giants is elliptical indicates that these objects do *not* form a spherical halo around M33 but instead consist of a relatively flattened distribution; whether it is as flat as the system of spiral arms is not clear from the present material.”

1.6 Summary

The bulge of M31 was the first extragalactic object seen by the unaided eye in the northern hemisphere. The bulge of the Milky Way was visible for anyone from ancient times onward to see on a clear dark night in the (northern) summer months. The natural correspondence between these two features was not obvious until well into the twentieth Century, so it should come as no surprise that there was no common term being used to describe them both. When discussing the Milky Way, the feature called the “Galactic Bulge” seemed to find its place in astronomical parlance far sooner and with far less equivocation than the multitudes of ways in which the same feature was described in an extragalactic context. In the Galactic setting the Galactic Bulge became a name, albeit a name with descriptive content. Once named, the feature became synonymous with what otherwise would have been one of many ways it could have been described. In the extragalactic context things were still very much in a state of flux, features, names and descriptions included. When Baade described bulges in other galaxies his language was more metaphorical than precise. It was meant to paint an image in the mind’s eye of the reader rather than be seen as a well defined and carefully thought out definition of a class. Be it “lens”, “bulge”, or “amorphous central region” the reader gets the general idea without anything quantitative being measured or implied. Inevitably this all changed as the study of galaxies became more quantitative and especially when digital detectors arrived on the scene. Loose terminology based on visual impressions gave way to quantitative measurements of features and components that could repeatedly identified, deconvolved, extracted, defined and “decisively” named. Initially “bulges” and “discs” were all that you needed to characterize the radial profile of a galaxy. The “bulge-to-disc” ratio became a quantitative measure of all galaxies of all morphological types. Names followed the numbers. Common usage won over descriptive whim; no vote was called for and no declaration was officially made by the IAU. By the mid 1970s “bulges” and “discs” were the only remaining candidates on a ballot that was never cast.

However convoluted and painful it may have been to adopt a commonly accepted name for these features, our consensus does not guarantee uniqueness. The morphological features extracted from one- or two-dimensional images are not obligated to be made up of identical stellar populations, nor do they necessarily have the same histories and/or formation processes; they just happen to look alike, at this time in the evolution of the Universe as originally seen in some particular bandpass. As this volume attests, assessing the detailed stellar content and kinematics of bulges, predicting their future evolution, or modeling their assembly histories, growth and fate are today topics of interest and hot debate.

The early "galaxy morphologists" had no reason to go much beyond classification lightly embedded in a simple interpretive model. But whatever theory of bulge formation might have been offered, philosophers of science could have warned that those theories would fall prey to "underdetermination" by the data. As Pierre Duhem (1954) first noted for the physical sciences (and as Willard Quine (1951, 1975) later broaden and generalized the argument to the pursuit of knowledge in general) for any set of observations there will always be many theories that will be equally able to account for those facts. This is a problem if one is intent on selecting the best of a number of proposed theories (i.e., using the methods of *abduction*, developed by Charles Saunders Pierce, which is "inference to the best explanation"; see for instance Lipton (2004)), but there is an even more insidious problem looming when nature itself has actually taken multiple paths to arrive at apparently (or perhaps even virtually) indistinguishable endpoints. For the case in point, bulges might have formed in a monolithic fashion at one early point in time or they might have formed over an extended period. To Hubble, these two theories would have been decisively "underdetermined" by his classifications derived from photographic images. And now today there are theories of hierarchical assembly over considerable periods of time that are vying with monolithic collapse. And then too the heating of discs, the onset of instabilities, and the dissolution of bars, to name just a few "secular" processes, are also possible (probable?) contenders for modifying "bulges" and/or producing their close relative the "pseudo-bulges". The hope of "reducing" a theory of bulge formation and evolution down to a simple process or to a single input channel may, with hindsight, be found to be a quixotic adventure. Nature is not obliged to conform to the simplest or even the currently best explanations found by its scientists.

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