

THE STEBBINS GALAXY: THE ORIGINS OF INTERSTELLAR MEDIUM STUDIES IN THE SHRINKING SUPER-GALAXY

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Abstract: The development of photoelectric photometry as an observational technique by Joel Stebbins and his colleagues at the University of Wisconsin's Washburn Observatory made possible, in the early 1930s, a new approach to the effects, extent, and nature of interstellar matter. In a series of papers published between 1933 and 1936, Stebbins showed that the Shapley galaxy was too large by at least a factor of two and that the size of the Andromeda Galaxy had been significantly underestimated, thus considerably reducing the apparent discrepancy between the two neighboring galaxies. The outcome was not simply a recalibration of the Shapley model, but rather the replacement of the incongruously large and transparent super-galaxy by the modern concept of the Milky Way: a galaxy of size comparable to other spiral galaxies and, like them, containing significant quantities of interstellar dust and gas. This paper explores the role of Stebbins and his colleagues and their applications of photoelectric photometry in formulating the modern concept of our Milky Way galaxy.

Keywords: Stebbins, Shapley, interstellar matter, photometry, galaxies.

1 PRELUDE

Quotation from Elizabeth Huffer (wife of C. Morse Huffer): *There was one time I can remember Stebbins coming in saying "We shrunk the universe!" He had found out these obscuring clouds and that people thought the stars were so much further away and it was because they were going through this obscuring material and they were much closer than they thought they were. And he was absolutely jubilant to think that he had made a discovery.*

C. Morse Huffer (long time colleague of Stebbins): *Yes, he and Shapley were quite rivals. Shapley had got the length of the galaxy as 200,000 light years and Stebbins got it at 100,000.*

Elizabeth Huffer: *And, of course, Stebbins was right ... he was absolutely jubilant. You would go into that observatory and there was just a feeling of exhilaration. He had made a milestone and he knew it. (Huffer, 1977).*

2 INTRODUCTION

The discovery that the Sun is nowhere near the center of our Milky Way galaxy constitutes one of the most significant insights of 20th-century astronomy. It is one among several fundamental facts that define what we now mean by the very word "galaxy," a term whose modern meaning only began to emerge in the 1920s. Harlow Shapley (1885–1972), referred to in the quotation above, opened this new direction in the study of our Galaxy with his survey of globular clusters and construction of their relative distribution in three dimensions. But the Shapley Galaxy, as formulated by him, was a factor of two or three times too large, was transparent (effectively free of gas and dust), and was asserted by him to be fundamentally different

from such neighboring objects as the Andromeda Nebula, as it was then called. The structure, composition, and dynamics of a unique 'super-galaxy' as set out by Shapley would be very different from the throng of negligible wisps—the spiral nebulae and globular clusters—swarming about it. General accounts mention, often vaguely and in passive voice, that Shapley's dimensions needed correction. The nature of the 'corrections' to the Shapley Galaxy are rarely spelled out. In particular, who made these corrections, and how? As we see above, Elizabeth Huffer thought that Joel Stebbins (Figure 1) did it. Stebbins's triumphant "We shrunk the universe!" (as reported by Elizabeth Huffer) hints at the cosmological implications of the work, which not only corrected Shapley's conclusions, but opened the way to a view of a Universe filled with countless galaxies comparable to our own. Getting the dimensions of the Galaxy correct involved the first explorations of the interstellar medium with the new technology of photoelectric photometry. To understand the significance of the work of Stebbins and the other Wisconsin astronomers, we need first to see the stage that Shapley had set.

3 CONSTRUCTING THE SHAPLEY GALAXY

As early as 1917, Harlow Shapley, then working at Mt. Wilson Observatory, recognized the significance of the apparent asymmetry of the distribution of globular clusters for determining the location of our Solar System relative to the rest of the Galaxy. The distinct asymmetry of the distribution of globular clusters as seen in the sky had been established by others, such as Karl P.T. Bohlin (1860–1939), P.J. Melotte (1880–1961), and Arthur R. Hinks (1873–1945) (Jeans, 1929: 25; Smith, 2006: 320–321), but Shapley was the first to obtain distances to the

globular clusters. The result of those measurements provided a three-dimensional distribution of the globular clusters from which he drew bold conclusions about the size and structure of our Galaxy. Assuming that the globular clusters form a symmetric halo around the center of the Galaxy, their apparent distribution in our sky and, critically, their distances tell us that the Sun is far from that center, which must lie roughly in the direction of the constellation Sagittarius. This was a most important result and a transformative insight, which challenged the then current statistical models constructed, for example, by Jacobus C. Kapteyn (1851–1922) and Hugo von Seeliger (1849–1924), who had concluded that the Sun was more or less centrally located within the stars of the Milky Way. By 1918, using distances he had worked out for a large sample of the globular clusters, Shapley concluded that the Sun was some 20,000 parsecs from the center of the distribution of the globular clusters, and that this distribution coincided with the general extent of our Galaxy, making the latter as large as 100,000 parsecs in diameter, although he reduced this to a value of about 60,000 parsecs in later publications (Shapley, 1918: 3–5).

3.1 Shapley's Methods

Shapley based his conclusions for the size of our Galaxy and the Sun's location within it on three fundamental arguments for the distances to globular clusters:

- 1) He found a way to recalibrate the period-luminosity ($p-l$) relationship discovered by Henrietta Leavitt (1868–1921) (for the Cepheid variable stars in the Magellanic Clouds) so that absolute magnitudes could be determined from observation of the periods. Using globular cluster Omega Centauri he extended the $p-l$ relationship to the cluster variables. Applying the $p-l$ relationship to a globular cluster in which periods could be determined for one or more variable stars, he could find the absolute magnitude of a variable star from its period and then use the difference between the absolute and apparent magnitudes to calculate the distance (Smith, 1982: 73–75).

- 2) For distances to globular clusters in which periodic variables could not be found, Shapley applied a statistical measure assuming the constancy of the mean absolute magnitude of the 25 brightest stars in the cluster, omitting the brightest five stars. Calibrating this measure by the globulars that succumbed to argument 1) allowed him to establish distances to dimmer, more distant clusters.

- 3) To extend the distance scale to clusters too dim for the use of argument 2), he took the absolute diameter of globulars to be roughly

constant and inferred the distances from their apparent diameters, calibrated from the cluster distances known from the previous arguments.

In this way Shapley established a 'distance ladder', which gave absolute distances to the globular clusters. Combining the distances with the known positions in the sky allowed him to construct the three-dimensional distribution of the system of globular clusters and gauge the distance of the Sun from its center; assuming that our Galaxy was roughly co-extensive with the system of globulars allowed him to establish the rough size of the Galaxy (Shapley, 1918: 2–3).

3.2 Shapley's Conclusions

As with any such scheme, the distances of the more distant objects will depend on the accuracy

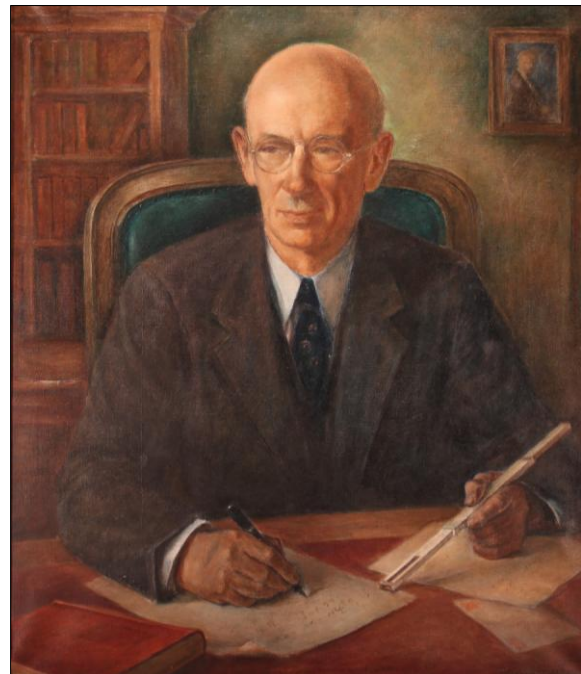


Figure 1: Joel Stebbins (1878–1966) in an undated portrait by Roland Stebbins (courtesy: University of Wisconsin-Madison Department of Astronomy).

racy of the distances measured to the closer objects as well as the validity of the methods used in reaching the higher rungs of the ladder. Shapley explicitly assumed that interstellar extinction was insignificant in applying his sequence of distance measures and that no systematic correction for it was necessary. He acknowledged, as was obvious, that there were dark, probably opaque clouds visible among the stars, but he considered their effects to be limited to small parts of the sky and thus avoidable. This would mean trouble if interstellar extinction turned out to be widely distributed and significant, because then distance would not be the only factor in determining the apparent brightness of distant objects such as the stars of globular clusters.

From that foundation he began drawing conclusions, which evolved over a series of publications into a model commonly called the “Shapley Galaxy.” His central conclusions, which he defended in print until 1930, can be summarized as follows:

- 1) The distribution of globular clusters, presumed to be centered around the center of mass of the Galaxy, shows the Sun to be far from that center.
- 2) The measured distances to globular clusters show the Galaxy to be about 70,000 parsecs (200,000 light-years or so) in diameter (Shapley, 1930a: 221). This is about twice the modern figure for the luminous Galaxy. In his earlier publications, as mentioned above, estimates as large as 100,000 parsecs diameter can be found (Shapley, 1918: 5).
- 3) Compared to other objects near our Galaxy (for example the Andromeda Nebula, whose distance and size were thought to be roughly known), our ‘galactic system’ is larger by perhaps an order of magnitude, hence probably fundamentally different in nature from the spiral nebulae (Shapley, 1930a: 179, 210).¹

3.3 Shapley’s Cosmology

Shapley drew cosmological implications from his conclusions, that is, he formulated ideas about the general structure, dynamics, and evolution of the Universe from his scheme of the super-galaxy, which he suspected was practically the entirety of the Universe in itself. One example is the question of the multitudinous spiral nebulae (for which there were few clues to actual distances), which many astronomers thought were galaxies comparable to our own. If they were comparable super-galaxies, then their apparent diameters implied that they were vastly more distant—hundreds of millions of light years—than Shapley thought reasonable (Shapley, 1919: 266). Therefore, Shapley concluded, those spiral nebulae must instead be relatively small, nearby objects, not like the super-galaxy of which the Sun is a member. This view was supported by the then credible observations of rotations, or perhaps internal proper motions, found in spiral nebulae by Adriaan van Maanen (1884–1946), which were consistent with the small size and distance of these objects relative to the super-galaxy. The questions one might ask about the dynamics and evolution of such a Universe, and the relevance of observations of the spiral nebulae, are very different from the approaches one would take if the spiral nebulae are actually comparable to our Galaxy.

Shapley was not shy about floating even more speculative hypotheses, albeit clearly labeled as such, connected to his super-galaxy.

He posited evolutionary paths connecting spiral nebulae, globular clusters, and open clusters, and mysterious gravitational and even ‘electrical’ forces in the equatorial disk of the super-galaxy to explain why spirals and globulars are not seen near the plane of the Milky Way (Shapley, 1918: 14). Thus the Shapley super-galaxy, as Shapley presented it, was far-reaching: a visible Universe dominated by a discoidal super-galaxy of stars or star clouds (in which we find ourselves closer to the edge than to the center) with a vast halo of indefinite extent populated by the diminutive spiral nebulae and globular clusters and shaped by vast forces hitherto unsuspected. Such extravagant theorizing attracted international attention, both positive and negative, from European astronomers such as Antonie Pannekoek (1919), Willem J. A. Schouten (see Smith, 2006: 321), Cornelius Easton (1921), and August Kopff (1921).

3.4 Shapley’s Galaxy under Siege

But already by the mid-1920s, the Shapley super-galaxy was in trouble in the view of many astronomers. First, there was the nature of the spiral nebulae. In 1923, Edwin Hubble (1889–1953) identified Cepheid variables in the Andromeda Nebula (Hubble, 1925). The apparent magnitude of those stars seemed to show that this ‘nebula’ was likely much farther away and hence larger than seemed consistent with the Shapley model. At about the same time there were growing doubts over the value of Van Maanen’s results, thus undermining their implication of the relatively small sizes and distances of spiral nebulae (Berendzen and Hart, 1973; Hetherington, 1974). Taken together these results helped reinforce the inclination of many astronomers to understand the spiral nebulae as vast stellar structures (‘island universes’ as they said) and perhaps even galaxies comparable to our own.

Moreover, between about 1928 and 1930, the work of Bertil Lindblad (1895–1965), Jan Oort (1900–1992), and John Plaskett (1865–1941) made a convincing case that they had detected and measured rotational motion of our Galaxy. While it was generally agreed that the evidence of the rotation placed the Sun far from the center of the Galaxy, Oort’s calculation of the distance based on the rotation was only about one-third of Shapley’s distance (Smith, 2006: 326). If the discovery of galactic rotation could be seen as confirmation for Shapley’s views, it was only in respect of the issue of the relative position of the Sun within it.

So Shapley was forced to back away from the view of spiral nebulae supported by Van Maanen’s work, which had “... gone down under the weight of novae and variable stars.” (Shapley, 1930a: 195–196), and admit that at least some were stellar in composition and not minor

gaseous satellites of the super-galaxy. Nevertheless he was still making a case for the super-galaxy. He continued to assert as late as 1930:

1) The center of the Galaxy lies about 16,000 parsecs (pc), or about 50,000 light years (ly), from the Sun (Shapley, 1930a: 221).²

2) The diameter of the Galaxy spans about 70,000 pc, or about 230,000 ly. (ibid.).³

3) Our own Galaxy is at least five times larger in diameter than the Andromeda Nebula, which is itself probably much larger than more typical spirals (Shapley, 1930a: 179). Indeed,

The lack of comparability between galactic system and spiral nebula appears now more certain than before; ours is a Continent Universe if the average spirals are considered Island Universes. (Shapley, 1930a: 195).

Shapley was well aware that his cosmic conclusions were only valid if his distances to globular clusters were trustworthy, and his methods assumed that any interstellar absorption of starlight was negligible. For that reason he included a chapter on "The Transparency of Space" in *Star Clusters* summarizing and expanding upon the defense of this assertion he had been making since 1918. He noted that such extinction could be both 'differential' (i.e. wavelength dependent, like Rayleigh scattering) and 'undiscriminating' (if produced by relatively large particles). The differential extinction would reveal itself in the colors of faint and distant stars, he pointed out, and indeed, globular clusters themselves, because of their visibility across great distances, should be good probes of differential absorption (Shapley, 1930a: 116). He compared the mean color indices (a measure of an object's color then made photographically) of samples of stars from three globular clusters: M3, M13, and NGC7006. NGC7006 lies about four times farther away from us than M3, and seven times farther than M13, but the stars of the most distant cluster are not, he concluded, significantly redder than the stars of the nearer clusters.

He also cited the lack of reddening of some extra-galactic nebulae, which are many times farther from us than the globulars, and concluded,

Apparently, we need not disturb ourselves further about the general dimming of light in space, even when dealing with external systems, unless it happens that the diminution differs from molecular scattering and has no effect on colors. (Shapley, 1930a: 121).

The lack of reddening in globular clusters and his conclusion that apparent diameters of globular clusters seem to decrease in proportion to their apparent brightness indicate "... the essential transparency of space up to a distance of 100,000 light years." (Shapley, 1930a: 120–121). This line of reasoning is entirely consistent with

his publication, with Helen Sawyer, (Shapley and Sawyer, 1929) in which, more than a decade after his first results, they published a new list of globular cluster distances based on recent studies on cluster stellar magnitudes, diameters, and variable stars. But there the possible issue of interstellar absorption in finding globular cluster distances is not even mentioned. In fact, although they revised Shapley's earlier cluster distances downward by 11%, they actually held out the possibility that recalibrations of the period-luminosity relationships for variable stars might even increase the distances again.

But in fact, interstellar matter and the reddening and extinction of starlight it causes are, as we will see, very significant. Why did Shapley conclude that extinction is negligible? His argument considered only three globular clusters: M3 and M13 are high in galactic latitude, +79° and +41° respectively, and NGC7006 is at -20°, which is well out of the Galactic Plane, where, as we shall see, the greatest reddening is found. Moreover, NGC7006 is near 64° galactic longitude (on the other side of the sky from the Galactic Center in Sagittarius) where the Milky Way is relatively narrow. Over there, 20° of latitude puts an object pretty well clear of the obscuring parts of the Milky Way. Shapley chose to look for a distance dependence on the assumption that selective scattering would be independent of location on the sky; he also chose a very small and rather idiosyncratic sample of clusters to examine; and his measure of reddening depended on the photographically determined mean colors of the brightest stars in a cluster, which were not necessarily typical.

In the same year that Shapley published *Star Clusters*, 1930, Robert Trumpler (1886–1956) demonstrated that interstellar extinction in the Milky Way was not, as Shapley had asserted, negligible (Trumpler, 1930a). Trumpler, working at Lick Observatory, photographically surveyed open clusters and showed that interstellar extinction resulted in overestimation of their actual distances. Moreover, he showed that this effect of interstellar matter amounted to about 0.7 magnitudes per 1000 parsecs (see, for example, Verschuur, 1989: 106ff). Trumpler's finding, while unambiguous about the extinction caused by interstellar matter, could not be applied directly to its effects on individual globular clusters. But there could be no question that Shapley's distances to globular clusters, the bedrock of his super-galaxy and the Universe it implied, had to be re-examined. So how far away are those globulars, and how large is our Galaxy?

4 THE WASHBURN OBSERVATORY RESEARCH PROGRAM

The excitement and triumph so clearly expressed in Elizabeth Huffer's account of Stebbins' (unfortunately undated) exclamation about the shrinking galaxy was surely a reaction to his success in showing that measurement of interstellar extinction could produce a better idea of what our Galaxy is really like than what Shapley had concluded. What exactly were the results that produced such exhilaration at Washburn Observatory? How did they come about, and how did other astronomers learn of these results?

The pioneering work by Stebbins in the field of astronomical photoelectric photometry has been recounted in several places (e.g. Hearnshaw, 2005; Leibl and Fluke, 2004; Susalla and Lattis, 2010). And it is for that work that he is best known. Stebbins and his colleagues at the University of Illinois, most notably physicist Jakob Kunz (1874–1938), had developed photoelectric

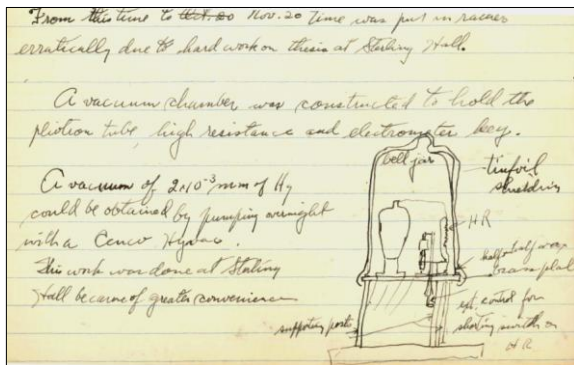


Figure 2: Albert Whitford's sketch of his prototype amplified photoelectric detector (courtesy: University of Wisconsin Archives).

detectors suitable for astronomical work starting about 1913 and began applying them to photometric research, particularly measuring light curves of eclipsing variable stars (Beaman and Svec, 2012). Stebbins moved to the University of Wisconsin's Washburn Observatory in 1922. There he continued improving instrumental techniques, such as more sensitive electrometers to measure the minuscule photocurrents of Kunz's detectors, and applying the techniques to new problems, most notably, for the current topic, filter photometry to measure color indices of stars.

A major step in increasing the sensitivity of the Washburn photometric instruments came in 1932 when Stebbins' young colleague Albert Whitford (1905–2002) succeeded in integrating within a vacuum chamber the photo-detector with a DC amplifier for the weak photocurrents (Figure 2). This had the effect of improving the sensitivity, on a given telescope, by about two stellar magnitudes compared to the older type instrument using only an electrometer.

The research program that Stebbins and col-

leagues Huffer and Whitford pursued starting in about 1930 was motivated, according to Stebbins, by his discussions of interstellar extinction with Trumpler, then at Lick Observatory, where Stebbins had long-standing connections. Trumpler and Stebbins were certainly not the only astronomers concerned about the effects of interstellar extinction. In fact, it had been raised as a potential weakness of Shapley's globular cluster distances not only by Shapley himself but also by A.C. Crommelin (1922), and by P.J. van Rhijn (1928: 123), who noted:

The subject seems of special importance because neither the distances of globular clusters and spiral nebulae nor the density of the stars per unit of volume in the galactic system can be found without an accurate knowledge of the quantity of light absorbed per unit of length.

Trumpler's definitive result established the subtle effects of interstellar absorption to nearly everyone's satisfaction. Stebbins decided to apply his unique abilities in photoelectric photometry to measurements of the reddening of starlight from individual globular clusters as a measure of the interstellar absorption.

Reddening would be one possible result of the passage of starlight through interstellar matter, depending, in the first approximation, on the sizes of the particles in interstellar space. Gas molecules or very small particles should, presumably, scatter shorter (bluer) wavelengths of light more effectively than redder light—just as Earth's atmosphere reddens the Sun at rising and setting by preferentially scattering the bluer light away from the line of sight. The proportion of light lost to wavelength-dependent scattering (or 'selective absorption') relative to the total absorption should be determined by the composition of the interstellar matter, including factors such as the proportion of gas to solid particles and the size distribution of the solid particles. Particles of relatively large size compared to the wavelengths of light would be responsible only for non-selective absorption. The amount of reddening, then, of a star's light should correlate somehow with the amount of matter, its physical characteristics, and its composition along the line of sight to the star and therefore to the total extinction, that is, the reduction in the apparent brightness of the star. Since interstellar absorption, as Trumpler had shown, was significant, it was clear that distance was not the only factor determining an object's apparent brightness. The total extinction is hard to measure, but reddening, they hoped, which could be measured, should act as an indicator of the total extinction. Indeed, Trumpler had already suggested in print that selective absorption should be seen strongly in dim (i.e. distant) stars at low galactic latitudes (Trumpler, 1930a: 223). Stebbins would

substitute globular clusters for the dim stars.

Stebbins seems to have decided right away on a two-pronged approach. He would measure the reddening of globular clusters, but he would also investigate the reddening of B-type stars, which are highly luminous and therefore visible across great distances, much brighter in our sky than typical globular clusters, and much more common than globular clusters. Measuring the reddening of B-type stars as a function of galactic longitude and latitude would roughly map the absorbing interstellar matter in the vicinity of the Sun. Measuring the reddening of light from globular clusters would probe greater distances and reveal whether Shapley's distances, and hence his conclusions about the location of the Sun and the size of the Galaxy, were correct. Comparing the reddening patterns of the two sets of objects would provide a check on the general approach.

Stebbins used a technique for measuring colors worked out by his predecessors in photoelectric photometry, Berlin astronomers Paul Guthnick (1879–1947) and Kurt Felix Bottlinger (1888–1934) (Whitford, 1978: 302). The general method, for both B-type stars and globular clusters, and regardless of which combination of instruments and telescopes the Washburn astronomers used, was to obtain a photometric magnitude measurement for a given object in two color bands defined by a 'blue' and a 'yellow' filter. The arithmetic difference between the two measurements provides a 'color index' that quantitatively characterizes the color of the object.⁴ Stebbins' filter choices were constrained by the limited color sensitivity of the Kunz photoelectric cells. The filter bands had to remain close enough to the detector's peak sensitivity to detect dim objects, yet be separated enough to make meaningful color distinctions.

In general the B-type star and globular cluster observing programs ran in parallel between about 1930 and 1936. C. Morse Huffer (1894–1981) led the B-type star observing in Madison using the 15.6-in refractor at the Washburn Observatory and an electrometer-equipped photometer. Stebbins, later joined by Whitford, did most of the globular cluster observing, mainly with the 100-in Mt. Wilson telescope. As a research associate of the Carnegie Institution since 1931, Stebbins had access to the Mt. Wilson telescopes. Moreover, Mt. Wilson astronomers Walter Baade (1893–1960) and Edwin Hubble saw great potential in the techniques of photoelectric photometry and urged Stebbins to bring his work there (Sandage, 1961: 118). Early on, Stebbins used an electrometer-type photometer for the globular clusters, but he switched to the more sensitive amplifier 'outfit' (as Whitford liked to call it) for the later measurements. And in a

departure from the reddening theme, Stebbins and Whitford carried out one more observation program to take on a key claim by Shapley—namely that the Andromeda Nebula, as it was known then—was considerably smaller than our own Galaxy. They used Whitford's amplifier outfit to make brightness profiles that could reveal subtle details invisible to conventional photography.

5 THE CAMPAIGN

The principal results of the Washburn Observatory program to investigate interstellar absorption emerged in a series of publications between 1933 and 1936. They first took on those problematic globular clusters that lie at the heart of Shapley's argument and measured the effects of interstellar absorption on their light showing that they are not only reddened but that the degree of reddening is dependent on galactic latitude. The second and third papers, on 'space reddening' in B-type stars, demonstrated an absorption pattern consistent with that found in the globular clusters, showed its general but irregular extent, and provided a broader mapping of the absorption effects across the sky. The fourth paper applied photoelectric photometry to measuring the extent of the Andromeda Nebula. The final paper in this group returned to the globular cluster question with new observations, presented an improved model of the distribution of interstellar matter in the Milky Way, and concluded by deriving some properties of the interstellar medium based on the spectrophotometric observations.⁵

5.1 Reddening of Globular Clusters

The very first paper in this series (Stebbins, 1933) proceeded quickly to the task of correcting the Shapley distances to globular clusters. The paper is by Stebbins alone and it presented results on the reddening of globular clusters acquired by him mostly in June and July of 1932, but with some as early as September the previous year. He used the older style electrometer instrument (the same well-understood device he had been using for years at Madison) on the Mt. Wilson 100-in telescope. His instrument, as in all the subsequent papers considered here, had a Kunz-made argon-filled photoelectric cell with a potassium hydride cathode at its heart. Such a cell had a peak sensitivity at about 4500 Å. In this work he used two filters, centered at 4300 Å and 4800 Å, to derive color indices for the globular clusters. On the scale he established for this work, a blue star with spectral type B5 has a color index of -0.36 , while a red star with spectral type K5 has a color index of $+0.25$.⁶ Stebbins acknowledged that more widely-spaced spaced filter bands would be more sensitive to measuring color indices, but explained the choice

as a result of the Kunz tube's sensitivity peaking relatively narrowly in the blue:

This amount [of wavelength difference between the filter bands] is not a large leverage for the determination of color indices, but it maintains the possibility of reaching faint objects. (Stebbins, 1933: 222)

It was entirely typical of Stebbins to accept the narrow constraints of a novel technique (as with his early photometry of eclipsing binary stars) and nevertheless produce good science by assiduous observing, careful methods, and minute attention to experimental error.

With this method he was able to determine color indices for 47 globular clusters, some as dim as magnitude 13.0, with a probable error in the color index that he estimated at ± 0.055 mag. Although, as he noted, it would have been better to measure the reddening with respect to the individual spectral types of the clusters, no spectra were available for such dim, diffuse objects as globular clusters. In effect, he was measuring

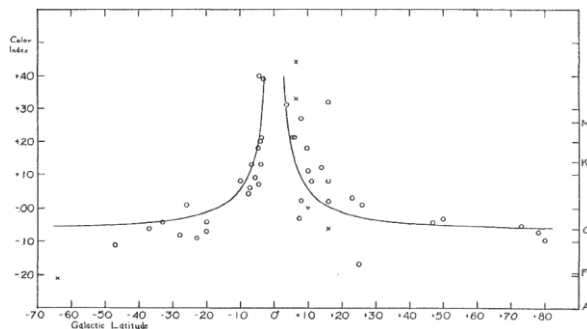


Figure 3: Globular clusters become strongly redder toward the plane of the Milky Way. The solid curves are independent fits, for northern and southern galactic hemispheres, of a cosecant function of galactic latitude. (after Stebbins, 1933: 225)

the redness of the clusters with respect to each other and looking for a correlation of the reddening with location on the sky. Based on the uncorrected color indices and the assumption of a thin, homogeneous absorbing layer near the Galactic Plane producing a differential reddening effect, Stebbins fit the data to a model describing a mean coefficient of absorption as a function of the cosecant of galactic latitude (Figure 3), and thus demonstrated that selective absorption shows a functional dependence on galactic latitude. The reddening of the globular clusters nearer the plane of the Milky Way is consistent with a layer of interstellar matter in the plane of the Galaxy, some component of which scatters preferentially at shorter wavelengths.

From his model for the absorbing region, idealized as a uniform layer extending some distance above and below the plane of the Milky Way, Stebbins derived its equivalent thickness to be 540 ± 60 pc. This, he noted, is about twice what Trumpler arrived at on the basis of his

open cluster studies and about three times that derived by van de Kamp. Peter van de Kamp (1901–1995), like Stebbins, had done his Ph.D. work at Lick Observatory and knew Trumpler well. Van de Kamp also had a doctorate from Groningen University completed under van Rhijn, who had earlier published on the problem of interstellar absorption. Like Stebbins, van Rhijn and others, van de Kamp (1930: 159) had concluded that

... our knowledge about the structure of the universe in low galactic latitudes depends essentially on our knowledge about the distribution and density of the galactic absorbing medium. A thorough study of the latter seems very desirable.

Like Stebbins, van de Kamp specifically mentioned Shapley's results as the target of the study. Van de Kamp in 1930, as Stebbins did in 1933, modeled interstellar absorption (although using photography to gauge the total, not selective, absorption) as a function of the cosecant of galactic latitude and had published, in 1932 and 1933, revisions to Shapley's globular cluster distances that yielded a distance from the Sun to the Galactic Center of about 5,500 pc. Stebbins was clearly far from alone in attempting to rein in Shapley's super-galaxy, but he was unique in applying the new technology of photoelectric photometry, which then produced results that conventional photographic techniques had not succeeded in doing.

Compared to Trumpler and van de Kamp, his own much larger result for the extent of the reddening layer, Stebbins suggested, came from the fact that the globular clusters are probably distant enough to show effectively all the absorption in the galactic system. But then to the heart of the matter:

We now proceed to apply these results to a correction of Shapley's distances of globular clusters, which were derived on the assumption of transparent space. (Stebbins, 1933: 225).

Applying a magnitude correction based on his cosecant model for space absorption, Stebbins calculated new distances to the globular clusters by adjusting Shapley's distances. The overall effect was that distances to globulars closer to the plane of the Milky Way were much less than Shapley had calculated and much more than van de Kamp had concluded using his measures of total absorption. Thus, "The center of the system, which Shapley placed at 16,000 pc, is now found at 10,000 pc from the sun." (Stebbins, 1933: 226). This finding, Stebbins (*ibid.*) noted, had cosmological implications:

The relatively large size of our own galaxy [according to Shapley's model] has long been an obstacle in considering it as a system quite similar to the extra-galactic nebulae, but this

difficulty is to a great extent diminished when the inferred dimensions of the galaxy are corrected for absorption.

In his conclusion, Stebbins summarized the significance of these first results of his measurements of interstellar reddening and its effects: 1. Distances from some globular clusters are only one-fourth the distances that "... have sometimes been supposed." 2. "The diameter of the galactic system of stars is reduced from 80,000 to possibly 30,000 pc." 3. "The great difference in size between our own galaxy and other such systems largely disappears." (Stebbins, 1933: 227).

Stebbins was careful to point out that his method measured only selective absorption. But the absorption that produces the reddening is likely to be only one component of the total absorption. The total absorption (i.e. absorption-measured-by-reddening plus absorption-without-reddening) is what reduces the apparent magnitude of the globular clusters:

It may be noted that any obstruction in space in addition to that accompanied by scattering as shown by the reddening of clusters will require a further reduction of all distances based upon photometric considerations. (Stebbins, 1933: 227)

Not only was he preparing the reader for further shrinking of the Galaxy, but this brief reference to the composition of the interstellar absorbing material, along with the demonstration of its latitude dependence, presaged a more nuanced view that would emerge in the later papers. It also set a new direction in research, on the nature of the interstellar medium, that became a major theme of Washburn Observatory research (see Liebl, and Fluke, 2004).

5.2 Reddening of B-Type Stars

As with the question of globular cluster reddening, Stebbins cited his discussions with Trumpler in autumn 1930—just when Trumpler's definitive papers on interstellar absorption were appearing—as the stimulus for measuring color indices of blue (i.e. B-type) stars. Indeed, Stebbins noted that Trumpler had already given some thought (apparently unpursued) to measuring the reddening of B-type stars and had provided Stebbins with a short list of candidate stars. This was the beginning of the work that Stebbins and Huffer would publish in a series of papers documenting successively larger sets of B-type star color measurements. All of the thousands of observations were made with the Washburn Observatory 15.6-in refractor using the electrometer-equipped photometer. Stebbins noted that while the amplifier photometer (which Whitford was perfecting at Washburn just as the B-type star work was in progress) was more sensitive, its speed was no greater for moderately bright

stars, so the electrometer method was fine for this kind of measurement. The method was basically the same as for the earlier globular cluster work, although he chose filters centered at 4200 Å and 4700 Å for measuring the color index. Again, the spectral leverage was not optimal, but, "What the cell loses in leverage by having the spectral regions close together it gains in the greater precision of the measures." (Stebbins and Huffer, 1934: 219). Unlike the globular clusters, Stebbins could establish a 'normal' color index for a B-type star, which he did by adopting the mean of a group of B-type stars brighter than visual magnitude 6 and located more than 15° from the Galactic Equator.

The majority of the extremely laborious observing, which would eventually produce color indices for more than 1300 B-type stars, was carried out by Huffer, Stebbins' long-term colleague at Washburn Observatory. Huffer and his student observing assistants, with occasional participation by Stebbins, logged thousands of hours of photometric measurements between November 1930 and March 1932 to produce the results that appeared in the publications co-authored by Stebbins and Huffer in 1933 and 1934.

In beginning his discussion of the results, Stebbins first explicitly assumed that the reddening results from scattering by particles in the interstellar medium. But he noted that it was premature to discuss the nature of the particles, i.e. whether they are gas molecules or dust, because "... the first step is to find out just where and how much the reddening is." (Stebbins and Huffer, 1934: 244). But he did return eventually to the nature of the interstellar medium and the question of whether and to what extent the scattering medium is gaseous or particulate.

In regard to the 'where', the conclusions of the B-type star studies confirmed the globular cluster results but extended them across much more of the sky and allowed comparison with the band of the Milky Way where spiral nebulae were never seen—the 'zone of avoidance'. In fact, the reddening of B-type stars confirmed the

... existence of a thin layer of dark scattering material near the median plane of the galaxy. The reddened stars are practically all within Hubble's zone of avoidance of the extragalactic nebulae. (Stebbins and Huffer, 1934: 258).

They illustrated this in Figure 4, which shows three subsets of increasingly-reddened B-type stars in galactic coordinates. Hubble's 'zone of avoidance' (the irregular contours of which Stebbins took directly from Hubble) runs across the plot above and below the Galactic Equator, and

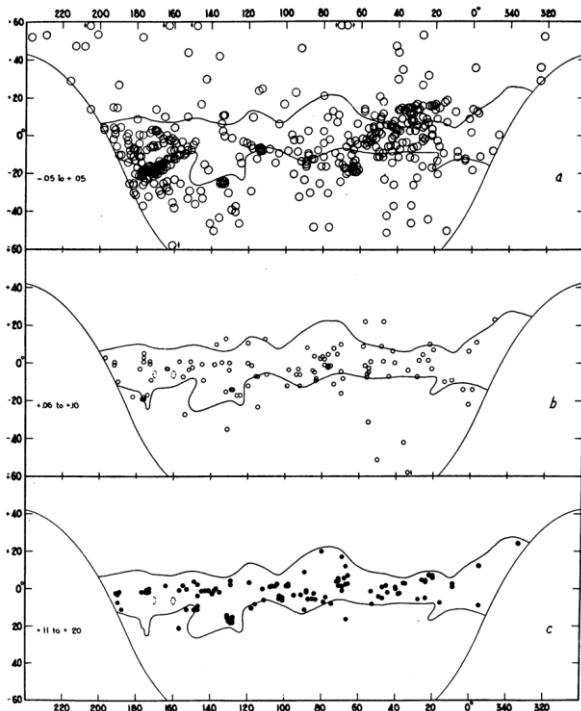


Figure 4: The more reddened B-type stars lie within the zone of avoidance (after Stebbins and Huffer, 1934: 242).

the curves cutting off the plot at right and left are the horizon cutoffs at the latitude of Washburn Observatory. Plot 'c' (the lowest) shows the reddened group of stars with color indices between +0.11 and +0.20, nearly all of which fall within the 'zone'. Subsets of increasingly-reddened stars are plotted similarly in Figure 5. Stars of color indices from +0.21 to +0.30 (top plot) concentrate still more toward the Galactic Equator, and in the reddest range, +0.31 to +0.55, the stars fall very close to the Galactic Equator.

'How much' was partly addressed in the lowest plot of Figure 5, in which the scale of galactic longitude remains the same, but the vertical axis now represents the amount of reddening per kiloparsec. The reddening climbs to-

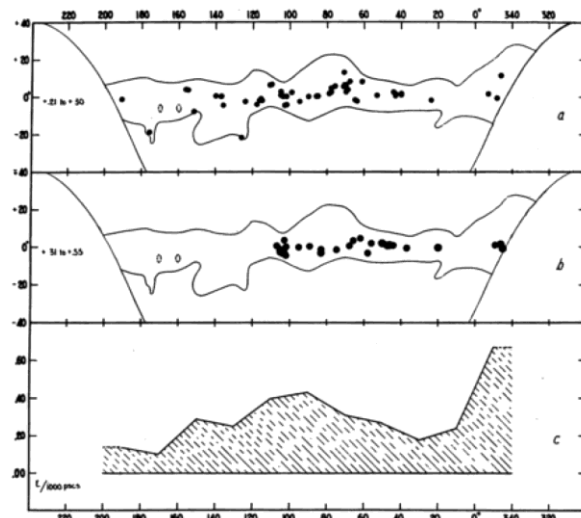


Figure 5: The most reddened stars and reddening along the Galactic Equator (after Stebbins and Huffer, 1934: 243).

ward a maximum approaching longitudes between 0 and 340° (near the center of the Galaxy), and descends to a minimum near the anti-center, near 180°. Despite these general trends, the distribution of space reddening, Stebbins and Huffer noted, is quite irregular as the reddening can be particularly strong in isolated regions. In fact, this is the first quantitative evidence for the extreme inhomogeneity of the general distribution of interstellar matter in the disk of our Galaxy. In addition, they pointed out that those areas of strongest reddening do not coincide with the visually-darker, more obscured, parts of the Milky Way but rather are found among the brighter star fields. They commented that although it is possible that the material causing the reddening might lie beyond the bright star fields, they thought it more likely that the material is in the spaces between the stars (Stebbins and Huffer, 1934: 248).

With reddening as measured by B-type stars mapped, the authors then proceeded to compare those results with the reddening of globular clusters measured by Stebbins. To do so they reduced the color excesses of the globular clusters to the scale used for the B-type stars and plotted them together in the region near the center of our Galaxy (Figure 6). The shaded strip along the Galactic Equator, where no globular clusters are found, is where the most reddened B-type stars—indicated by crosses—are found; and the reddening of the globular clusters tends to be greater as they are closer to that strip. In Figure 6, the filled circles indicate reddened clusters and the bigger dots mean more reddening.

This has important implications for Shapley's general system, which located a number of the globular clusters

... nearly in line with but far beyond the nucleus of the galaxy. On this view the light of the clusters comes through where the extragalactic nebulae are blotted out altogether. We think it more probable that the general region near the galactic center is opaque to the light of objects beyond the nucleus, and that the fainter globular clusters in that direction are between us and the center. (Stebbins and Huffer, 1934: 251).

So instead of seeing far across the entire expanse of a transparent Galaxy, as Shapley had thought he was doing, Stebbins and Huffer decided that we are actually seeing only objects on our side of the Galactic Center, and even those are very reddened. What is beyond is completely obscured by optically-opaque interstellar matter.

After a brief and inconclusive discussion of possible correlations between the reddening of B-type stars and the strength of interstellar calcium line absorption, Stebbins and Huffer implicitly turned their sights back to Shapley and the

size of our Galaxy. Although the B-type stars had revealed space reddening to be extremely irregular, which makes calculations of distance liable to large uncertainties, multiple lines of evidence mean "... practically complete obscuration of distant objects near the galactic plane." (Stebbins and Huffer, 1934: 255). Without any doubt, the amount of absorption near the Galactic Plane meant that the inferred distances of objects must be reduced: "The largest absorption for B-stars is about two magnitudes, photographic, which means a division of the distances by 2.5." (Stebbins and Huffer, 1934: 259). Thus,

The evidence from B-stars, from open and globular clusters, and from extra-galactic nebulae all agree in establishing the presence of the thin stratum of absorbing material near the galactic plane. There is every reason to conclude that this absorbing layer is quite similar to the dark lanes that we see in other galaxies that are viewed edge-on. When the absorbing effect of the dark material is properly allowed for it is expected that the hiatus between the dimensions of our galaxy and the other such systems will largely disappear. (ibid.).

With the confluence of the B-type star and globular cluster results, their case that interstellar matter has very important effects was now quite a strong one. Moreover, they made the point that our Galaxy would, if seen edge-on from outside, look similar to other spiral galaxies. Others had speculated in the same vein (for example, Curtis, 1917: 682; Trumpler, 1930b: 188), but unlike the others, Stebbins' comparison between our Galaxy and other spiral galaxies rested on new and solid evidence, and he presented it specifically as an alternative to the Shapley super-galaxy, both in terms of size and composition.

The aforementioned research was published first in *Proceedings of the National Academy of Sciences* (1933) and later in the *Publications of Washburn Observatory* (1934). For the most part, the two research papers parallel each other, and in many passages are identical. The Washburn Observatory version includes lengthy tables of stellar reddening data, which the *PNAS* paper omits. The only significant section that appears in the *PNAS* paper but was omitted from the Washburn Observatory version contains a discussion of the total mass of interstellar material responsible for the observed scattering. This discussion is very interesting as an early attempt to infer the amount of non-stellar mass in our Galaxy. There is no clue as to why it appears in only one version of the paper.

Stebbins and Huffer noted that they could go beyond earlier estimates of the mass of the interstellar absorbing material because the B-type star work had involved a survey of most of the plane of the Galaxy, whereas the earlier

attempts by Anton Pannekoek (1873–1960) and Arthur Stanley Eddington (1882–1944) were based on an extrapolation from a small portion of sky in Taurus. So

... now we have the whole mid-galactic layer filled with stuff and in a volume probably millions of times greater than the space in Taurus. (Stebbins and Huffer, 1933: 603).

Nevertheless, they noted that it remained premature to take the estimates very far because the ratio of total absorption to selective absorption was still unknown. Plunging ahead for the sake of illustration, they assumed the interstellar scattering through the entire absorbing layer along the line of sight perpendicular to the plane of the Galaxy to be of the same order as that produced by a column of terrestrial atmosphere looking toward the zenith, the cross-sectional mass of which they estimated at 1000 grams per square centimeter. Assuming the discoidal Gal-

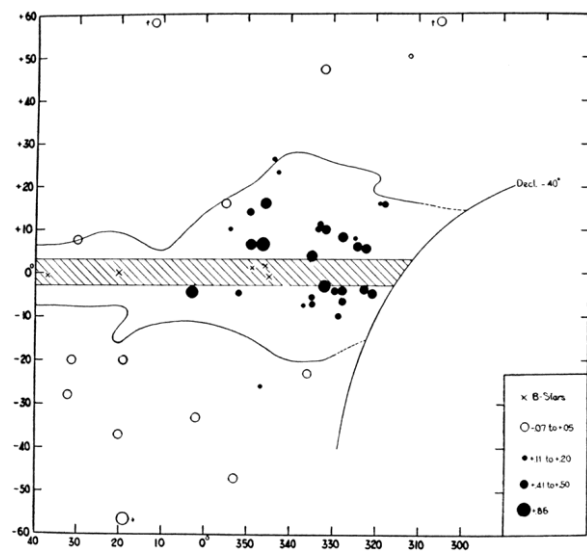


Figure 6: Reddened B-type stars (crosses) and globular clusters in and near the zone of avoidance in the region around Sagittarius (after Stebbins and Huffer, 1934: 251).

axy to be 30,000 parsecs in diameter (much smaller than the Shapley super-galaxy), the total mass in the absorbing layer would be $\sim 3 \times 10^{15}$ solar masses. This much mass seemed unreasonable.⁷ But the authors noted then that solid particles, compared to gas molecules, are more effective at scattering, per particle, by a factor of $\sim 3 \times 10^6$, which implies a total scattering mass of 10^9 solar masses multiplied by the (unknown) ratio of the mass of a typical scattering particle to that of an air molecule. So although the total stellar mass of the Galaxy, they noted, was quite uncertain, "On any calculation it will not be surprising to find the dark material greater in mass than the total of the stars." (Stebbins and Huffer, 1933: 604). In the Shapley super-galaxy, the amount of matter between the stars was considered to be insignificant, but in the smaller 'Stebbins galaxy', the non-stellar mass might actually exceed the combined mass of all the stars!

5.3 Taking the 'Hiatus' by Its Other End: The Diameter of the Andromeda Nebula

Stebbins pointed out that the 'hiatus'—that is, the apparent discrepancy between the estimated size of our Galaxy and the Andromeda Nebula—was quite large in the Shapley super-galaxy picture. It could amount to an order of magnitude, depending on which particular estimates of the sizes one takes. In his extensive study of that famous spiral nebula Hubble (1929: 156) concluded that "... the galactic system is five or six times the diameter of the spiral." In this estimate, he was depending on one of Shapley's results, based on globular cluster measurements, that the Galaxy was about 80,000 pc in diameter. Hubble realized that photographic limitations, such as sky brightness, probably caused the extent of the spiral to be underestimated, but his techniques could not correct for such factors. The Washburn astronomers' research had so far pointed to a considerable reduction in Shapley's size of our Galaxy, which had the effect of reducing the 'hiatus', but the true relative sizes of the two objects, and therefore the question of whether they are comparable objects or of different natures from each other, obviously depended also on the estimated size of that prominent nebulous object in Andromeda, which photography could not fully gauge. But the recently-developed amplifier photometer

could do the job.

Stebbins and Whitford obtained photometric brightness profiles of the Andromeda Nebula using their amplifier outfit on the Mt. Wilson 100-in reflector in spring and summer of 1933, although Stebbins had experimented with the photometry of 'extra-galactic nebulae' at Mt. Wilson in previous years. The photometer vacuum tank, containing the Kunz photoelectric detector and amplifier, was mounted at the Newtonian focus of the telescope. A cable connected that instrument to the galvanometer—which measured the photocurrents—at the base of the telescope pier (see Figure 7).

The method, as was nearly always the case in Stebbins' photometric work, was to make differential measurements, comparing, in this case, the brightness measured at a place on the nebula, with that of a nearby spot of clear sky. The difference between the two deflections indicated by the galvanometer was the fundamental datum. By this differential method they generally avoided complications of varying air mass, minor variations in detector sensitivity owing to temperature and battery voltage, and so on. Their ability to directly subtract the sky background was a considerable improvement over photography in the detection of very low-contrast objects, such as the periphery of a spiral galaxy. On a given

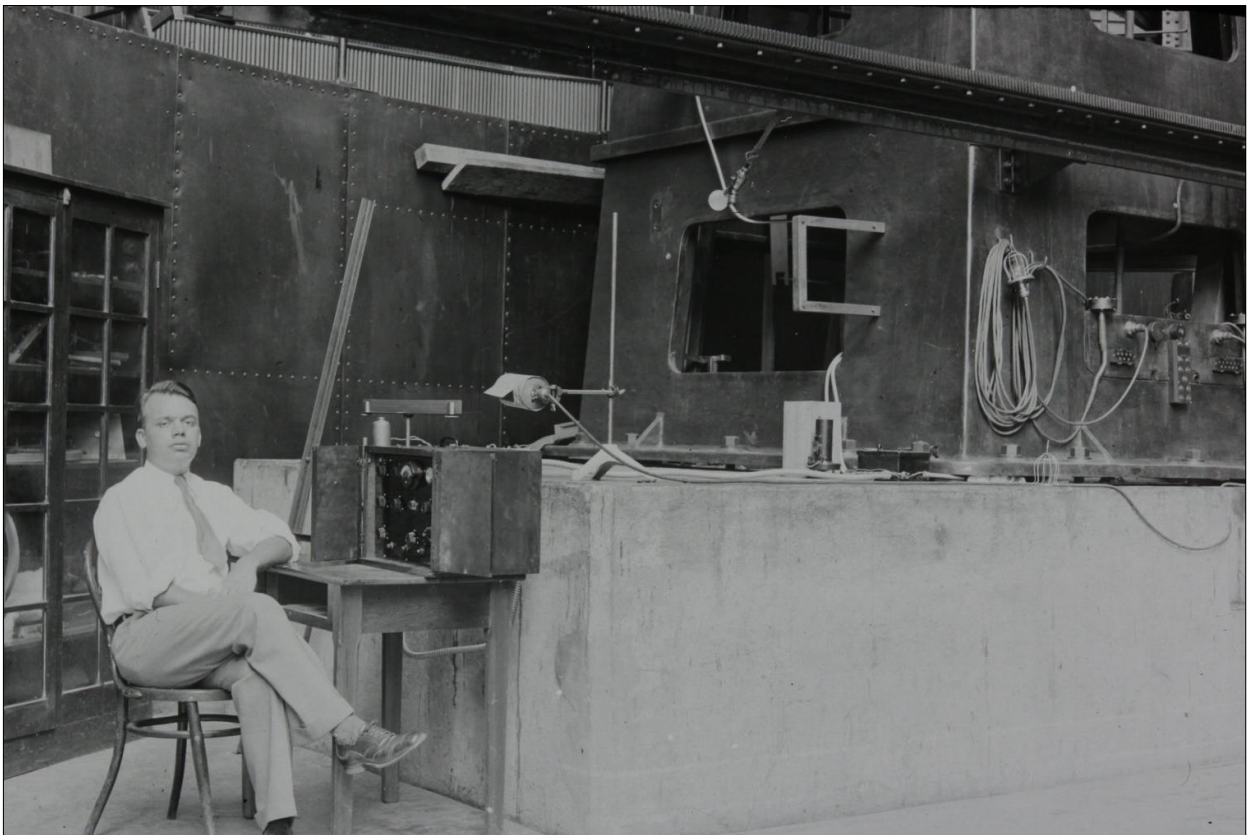


Figure 7: Albert Whitford at the readout position of his amplified photometer on the 100-in telescope. The galvanometer scale is the horizontal screen just above his table-top instrument cabinet, and the optical-lever galvanometer, the small dark vertical cylinder, sits on the top of the concrete platform half way between the galvanometer scale and the right edge of the photograph (courtesy: University of Wisconsin-Madison Department of Astronomy).

run they measured the differences between nebula and sky along linear paths crossing the nebula at increments of 10 arcmin in declination (see Figure 8).

In the paper setting out their results, published in 1934, Stebbins and Whitford established the context immediately as that of the notorious hiatus: "Any increase in the known size of extra-galactic nebulae is of course important in a comparison with the dimensions of our own galaxy." (Stebbins and Whitford, 1934: 93). After discussing the difficulty of comparing photographic measures of the dimensions, they concluded that their own measurements showed that the previously-accepted diameter of the Andromeda Nebula had to be at least doubled along the north-south extent, and that the same factor should probably also be applied to the perpendicular axis as well. Thus,

The present work indicates that the diameter of the nebula may well be as much as 20,000 pc ... [while] the figure for the [Milky Way] galaxy may have to be revised still further [downward] when the space absorption near the median plane is better determined ... In fact, when the size of our galaxy is as well known as that of the Andromeda nebula, most of the inferred difference in scale between the two systems may disappear. (Stebbins and Whitford, 1934: 98).

They also were ready to speculate that this result is probably typical of other spiral nebulae: "The extension of the Andromeda nebula beyond the photographic limits is presumably typical of what may be found for other such objects." (ibid.).

After 1952 and Walter Baade's recalibration

of the Cepheid period-luminosity curve, the distance, hence size, of the Andromeda Nebula based on Cepheids would be effectively doubled, confirming, as Stebbins expected, that it was comparable in size to our own Galaxy.

So the disturbing 'hiatus' introduced by the Shapley super-galaxy was unraveling at both ends because Stebbins and his colleagues had new data to cut it down to size. The intuition that there ought to be some uniformity in the nature of the spiral nebulae, and the disquiet at locating ourselves in a very special assembly of stars—the Shapley super-galaxy—had found new empirical support in the research program of the Washburn astronomers.

5.4 Finishing off the Shapley Galaxy: Back to the Globular Clusters

As the B-type star work continued at Madison, and the Andromeda Nebula measurements were in progress in 1933 on the 100-in telescope at Mt. Wilson (during which time Whitford was a National Research Council Fellow at Mt. Wilson), Stebbins and Whitford began using the same equipment on the 100-inch to begin new measurements of the colors of globular clusters. The result was a considerable expansion and improvement over Stebbins' 'preliminary report' of 1933. In the paper they published in *Astrophysical Journal* in 1936, Stebbins and Whitford reported colors of 68 globular clusters (increased from 47 in the 1933 paper). The new observations, acquired between 1933 and 1935, employed new filters (4340Å and 4670Å), which reduced the color index 'leverage' from 500Å, as in the earlier globular cluster and B-type star

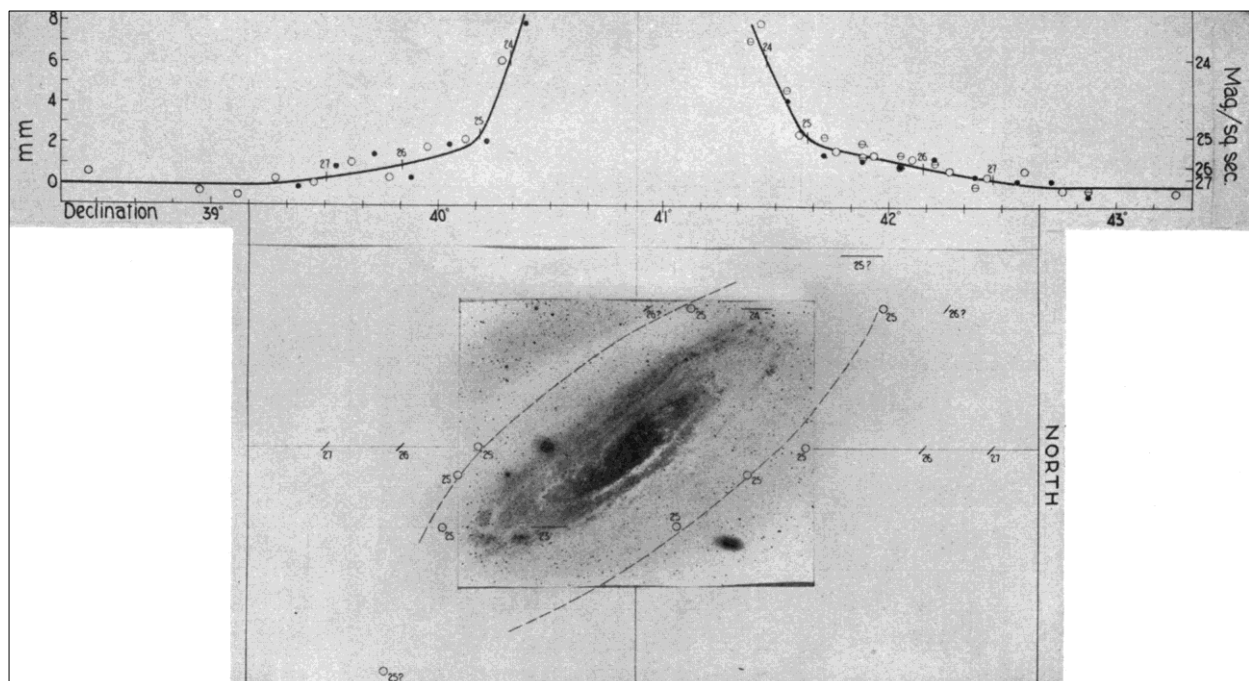


Figure 8: Illustration of photometric brightness contour along a north-south line through the nucleus of the Andromeda nebula. (after Stebbins and Whitford, 1934: 96).

work, to 330\AA . The authors explained that these choices produce equal deflections about spectral type G.

The effect of moving the filter centers closer to the peak sensitivity of the potassium hydride Kunz cell (about 4500\AA) meant greater sensitivity, important for the work on dim globular clusters. The lower noise levels of the photoelectric amplifier compared to the older electrometer rig compensated for the loss of leverage. The clearest indications of the technical advance were that the photoelectric amplifier could measure colors (on a given telescope) for objects a full magnitude dimmer than could be reached by the electrometer instrument, and that the probable error of the color measurements (as estimated by Stebbins) ranged from ± 0.01 to ± 0.04 mag with the new instrument compared to ± 0.055 with the older one.

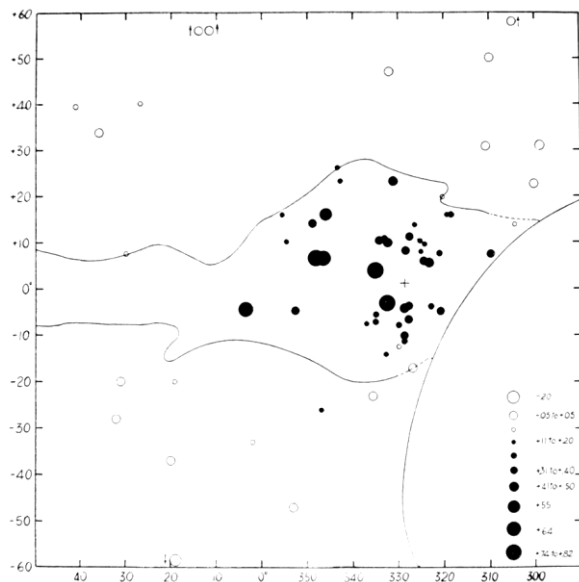


Figure 9: Color distribution of globular clusters. Reddened clusters are filled dots, with larger dots indicating greater color excess (after Stebbins and Whitford, 1936: 145).

In discussing the results, Stebbins and Whitford first compared their globular cluster colors with two other measures expected to be correlated with interstellar absorption: the number of nebulae in a given area of sky and the richness of the star fields. They acknowledged Baade in this comparison, who assisted them by examining his plates "... taken with the large reflectors ..." for the areas around a subset of the globular clusters.⁸ For each cluster, Baade had characterized the number of nebulae on the plate as 'normal', 'less than normal' or 'none', and he had characterized each star field as 'normal', 'partially obscured' or 'heavily obscured'. When the globular clusters were ranked in order of increasing color index (increasing redness), there emerged a fairly abrupt transition in the nebula counts at about color excess $+0.19$: plates containing clusters less reddened than $+0.19$ al-

most all showed 'normal' nebula counts in the area around the cluster, while those redder than $+0.19$ show 'none'. Only three of the 43 clusters with color excesses near $+0.19$, were found in areas with 'less than normal' nebulae. This was exactly what one would expect if the reddening of the clusters was a result of selective scattering by interstellar matter. As they wrote, "The close correlation of the colors with the numbers of nebulae is striking." (Stebbins and Whitford, 1936: 145).

Less striking was the relationship of star scarcity to cluster reddening, which showed only a general tendency for fewer stars in areas with more reddened clusters, which is consistent with the lack of a strong correlation that they had found between B-type star reddening and stellar density. The authors noted that rich star fields could lie in front of absorbing regions, which would blur the correlation, but they observed that whenever there was a relative scarcity of stars at low galactic latitudes, the globular clusters were strongly colored. In any case, the hypothesis that globular cluster reddening was caused by selective absorption in interstellar space was consistent with the rough measures of nebulae and star counts.

Stebbins and Whitford introduced their discussion of the general system of globular clusters with a diagram that plots the locations of clusters in galactic coordinates near the Galactic Center and indicates their degree of reddening (see Figure 9). This is very similar to the diagram published with the B-type star work (see Figure 6 above), but redrawn with more globular clusters and no B-type stars. The curve on the right is the horizon cut-off at the latitude of Mt. Wilson, and the Galactic Equator runs horizontally through the middle. Hubble's 'zone of avoidance' in the region of the center of the Galaxy contains nearly all of the reddened globular clusters, and the lower the latitude the redder the cluster. But along the Galactic Equator itself are no globular clusters are to be found. Putting this together with the correlation between cluster reddening, nebula counts and star counts, they declared: "There is now no doubt that Shapley's first distances of clusters must be corrected for absorption." (Stebbins and Whitford, 1936: 148). Figure 10 provides a modern illustration of the reddening effect.

What kind of correction should be made for the interstellar reddening? The choice was really between some kind of model for a coefficient of absorption, such as a cosecant law, as Stebbins discussed in his 1933 globular cluster paper, or applying individual corrections to each cluster according to how reddened it appeared. Stebbins and Whitford cited the attempt by Baade to model the absorption as a cosecant function of



Figure 10a: Three-color composite image of globular cluster M71 as it appears to us reddened by selective extinction in the interstellar medium. This cluster lies very close to the galactic plane and is so obscured that it was not even recognized to be a globular until the 1970s. For this reason M71 was not among the objects observed by Stebbins (courtesy: Bob Franke/Focal Pointe Observatory).



Figure 10b: The above image of globular cluster M71 processed to remove the calculated reddening, giving an impression of how it would look if seen through empty space (courtesy: Bob Franke/Focal Pointe Observatory). More information on these images is available at <http://apod.nasa.gov/apod/ap141210.html>.

galactic latitude, which came to the conclusion that "... practically all globular clusters are contained within a sphere of 20,000 pc radius." (Baade, 1935: 410). They modified Baade's numbers to derive a distance to the center of the system of globular clusters of about 8,000 parsecs. Nevertheless,

Other considerations, especially the distribution of colored B stars, have convinced us that the simple assumption of a uniform layer of absorbing material near the plane of the galaxy will not suffice ... at least there should be a dependence upon the longitude. (Stebbins and Whitford, 1936: 149–151).

The distribution of the reddening, as shown in Figure 9, demonstrates how 'spotted' is the pattern of reddening, with contrasting color excesses mingling within the zone of avoidance. After the B-type star work, this was yet another empirical demonstration of the extreme patchiness in the distribution of our Galaxy's interstellar matter, as well as an indication of how tricky it might be to model the absorption mathematically. So rather than a simple cosecant law,

Table 1: Comparison of distances to the center of our Galaxy derived from different assumptions about interstellar absorption (after Stebbins and Whitford, 1936: 156).

Photographic Optical Thickness (mag.)	Distance to Center (kpc)	Basis
0.0	16.4	Shapley, original moduli
0.32	10.0	Colors of globular clusters
0.50	8.0	Hubble's count of nebulae
0.8	5.5	Van de Kamp, Harvard counts of nebulae

Stebbins and Whitford proposed to take account of the irregularity of the absorption by using the reddening of the individual clusters to find the amount of absorption in the line-of-sight to each individual cluster, with the explicit assumption that

... the ratio of the selective to the general absorption is constant, that the relative proportion of the light-scattering particles and the light-obstructing particles is the same throughout the space considered. (Stebbins and Whitford, 1936: 151).

Establishing the value of this ratio was, however, not an easy task, because it involved comparing estimates of the 'photographic' absorption (as a measure of the total absorption) with the selective absorption (measured by reddening). The former came from counts by others (primarily Hubble (1934) and van de Kamp (1932; 1933)) of nebulae made in moderate to high latitudes, while the latter came from their reddened globular clusters, mostly at low latitudes. The details of the arguments are somewhat tedious, but in the end, Stebbins and Whitford (1936: 153) concluded that the value

... for the total photographic absorption, derived from the counts of nebulae, is three or four times the absorption we might infer from the reddening alone.

The authors turned immediately to the nature of the absorbing matter itself, repeating a conclusion from their paper on B-type stars:

In a discussion of the total amount of interstellar matter which causes space reddening it is necessary, in order to avoid an impossibly large mass, to suppose that the scattering material is composed largely of solid particles rather than gas molecules. It would indeed be surprising if some of the particles were not too large to scatter according to the Rayleigh law, and therefore merely obscure without reddening. (Stebbins and Whitford, 1936: 154).

Having recalculated the Shapley distance to each cluster according to the estimated total absorption, Stebbins and Whitford proceeded to test whether these new distances produce the expected 'system' of clusters symmetrically condensed about a distant center. But in fact, plotted this way, the grouping of clusters is still elongated, as Shapley had concluded, along the x-axis (the radius from the Sun toward the center of the Galaxy), which is both unsatisfying and unlikely (since it would seem to imply that the radius to the Sun is a special direction for the globular clusters). This suspicious elongation had been noted by others, including, for example, van de Kamp (1931) and Boris Vorontsov-Velyaminov (1930). Van de Kamp considered absorption a prime suspect. After calculating the corrections from colors of individual clusters, Stebbins and Whitford were so confident that the elongation resulted from systematic error that they concluded:

... the proper corrections cannot be made either from the cosecant law or from the colors, or else the original uncorrected distances are uncertain. (Stebbins and Whitford, 1936: 154).

They chose the last of these three options: Shapley's use of apparent diameters for judging the distances of the faintest clusters was subject to very large uncertainties, which were exacerbated, they pointed out, especially at low galactic latitude, by the effects of total absorption, which Shapley explicitly neglected. Nevertheless, one could still try to use the centroid of the distribution of the clusters to estimate the distance to the center of the system. So Stebbins and Whitford concluded their paper by presenting a short comparison of values of distances to the center of the system of globular clusters (and hence presumably the Galaxy) derived from different assumed values of total interstellar absorption (see Table 1). The first distance is from Shapley, whose cluster distances neglected any interstellar absorption. The second is the value arrived at by Stebbins and Whitford on the basis of

the reddening of the globular clusters. The third and fourth distances were deduced from the estimates of total absorption by Hubble and van de Kamp respectively. All three of the results that take into account some degree of interstellar absorption put most of the globular clusters within a sphere 30,000 to 40,000 pc in diameter (as determined by the maximum extent of the globular cluster system). In a final reply to Shapley, Stebbins and Whitford (1936: 157) wrote:

Our galaxy is a large one; but when its apparent dimensions are corrected for space absorption, and the extension of the Andromeda nebula, both in stars and in clusters, is considered, the two systems seem to be of the same order of size.

6 CONCLUSION

As we have seen, Stebbins and his Washburn Observatory colleagues were working to address the provocative cosmological implications of the super-galaxy, that is, they wanted to put the 'hiatus' on trial, to test whether our Galaxy was, as Shapley held, a monstrous continent among mere islands, or whether our Galaxy was, as intuition and evidence was telling many astronomers, something more typical. Shapley's location of the Sun far from the center of the Galaxy is sometimes portrayed as a triumph of the 'Copernican Principle', which had presumably been offended by our star's more central location in the Kapteyn galaxy. But if so, then the Copernican Principle should have been just as offended by the special status of the super-galaxy. Or, as Eddington (1933: 5) put it:

According to the present measurements the spiral nebulae, though bearing a general resemblance to our Milky Way system, are distinctly smaller. It has been said that if the spiral nebulae are islands, our own galaxy is a continent. I suppose that my humility has become a middle-class pride, for I rather dislike the imputation that we belong to the aristocracy of the universe.

Probably many astronomers agreed, and that would have been part of what fueled the 'Great Debate' as well as its aftermath.

What was emerging from the investigations provoked by Shapley's grand vision was a new concept of our Galaxy, much larger than Kapteyn's but much smaller than Shapley's, full of a lumpy distribution of non-stellar matter perhaps comparable in mass to the collective stellar mass; and comparable in size, structure and composition to neighboring galaxies. The new view of our Galaxy, outlined clearly in the work of Stebbins and others in the 1930s, included the interstellar matter that would later be recognized as essential not only for absorption and scattering of light, but for stars to form and spiral structures

to emerge. Perhaps most importantly, the emerging concept was of a Galaxy not fundamentally different from the neighboring galaxies, but rather enough like them to allow astronomers to study structures and processes that operate in our own Galaxy but tend to remain cloaked in the complex interstellar medium. If our Galaxy was a continent, astronomers were now gazing across the cosmic oceans onto the shores of countless other galactic continents.

Beyond resizing our own Galaxy and others, the work of the Washburn astronomers had yielded the first mapping and measurement of interstellar matter and generated some early insights into the nature of the interstellar medium. They would extend their work to include measurements of interstellar matter's extreme inhomogeneity and determination of the 'law of interstellar reddening', which is to say, the behavior of interstellar scattering as a function of wavelength.

The dismissal by Shapley of any significant interstellar absorption remains somewhat puzzling. As noted earlier, he was fully aware that interstellar absorption could undermine his methods, so he attempted to estimate its effects and, as we saw, deemed them negligible. Why did he find no reddening in the globular clusters and thus decide that interstellar absorption was a non-issue while Stebbins found, quite to the contrary, significant reddening? In part, the answer stems from Stebbins's decades of effort in developing his photoelectric techniques. Shapley had to depend on conventional photographic color indices derived from individual, faint cluster stars. But it is precisely here that photoelectric photometry had a considerable advantage over photographic photometry, because Stebbins could work with the integrated light of the entire cluster. In addition there was the thoroughness and methodical approach that Stebbins was known for: while Shapley dismissed the extinction problem after checking three globular clusters located in parts of the sky unlikely to show much absorption, Stebbins measured every globular cluster visible from Mt. Wilson. Moreover, he tested his cluster conclusions by checking the reddening results via the laborious B-type star program and also against, for example, Baade's counts of nebulae and star fields. Shapley's personal style seems to have been to forge on to grand hypotheses and leave their trials to others.

Even with the 'Great Debate' about the nature of the spiral nebulae resolved by Hubble, the apparent gulf in size between our Galaxy and the spiral nebulae, typified by the nearby Andromeda Nebula, remained a serious problem. Stebbins and his colleagues directed their efforts to the solution. But, as I have argued, there was more involved than a question of calibration and

spatial dimensions, because the resolution of the 'hiatus' required the recognition and understanding of the phenomena caused by interstellar matter, and that took Washburn Observatory's astronomers toward new investigations and a modern understanding of galaxies.

7 NOTES

1. An important early study of the Andromeda Nebula was by Hubble (1929), cited by both Shapley and Stebbins, but a common assumption was that if the spirals were 'island universes' then they would be at most the size of the Kapteyn Universe, which might be very roughly 10,000 parsecs in diameter.
2. Modern values disagree but locate the center of our Galaxy between 6,700 and 8,500 pc from the Sun.
3. It does not have sharp edges, of course, but modern estimates put the diameter of the baryonic matter in the Galaxy at between 100,000 and 120,000 ly.
4. This method predates both the six-color system developed by Stebbins and Whitford and the Johnson-Morgan UBV color indices of stars.
5. Some of these papers appear twice in the literature, once as a *Publication of the National Academy of Sciences*, from which Stebbins received occasional funding, and again as a *Contribution from Mt. Wilson Observatory*. I have cited the *PNAS* versions unless otherwise noted.
6. Relative reddening is equivalent to a more positive color index, hence 'color excess'.
7. It amounts to about a thousand times the modern estimated baryonic mass of the Galaxy.
8. Only 43 of the 68 for which they had colors appear on this list. Stebbins and Whitford gave no explanation for this, but perhaps Baade did not have plates on hand for all the clusters.

8 ACKNOWLEDGEMENTS

For their helpful discussions, comments and general assistance, I wish to thank John Gustafson, Randall Rosenfeld, Peter Sobol, Linda Sparke, Chris Sterken, Peter Susalla, Joseph Tenn and two anonymous referees. This research has made use of NASA's Astrophysics Data System and the University of Wisconsin Archives.

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