

V.M. SLIPHER'S DISCOVERY OF THE ROTATION OF SPIRAL NEBULAE AND THE CONTROVERSY WITH BERTIL LINDBLAD

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Abstract: A study of the Lowell Observatory Archives has revealed that, starting in 1917, V.M. Slipher worked out a coherent hypothesis concerning the rotation of spiral nebulae. When Hubble became interested in the question in 1932, he discovered Slipher's work, studied it and concluded, according to his own observations, that Slipher was right. Slipher's conclusions concerning the dynamics of the spirals were only called into question in 1940 when Lindblad claimed that the spiral arms were 'leading'. Hubble defended Slipher's conclusion, and Slipher himself intervened in the debate in 1944 with only a short note. The debate ended in part with the evolution of Lindblad's work and with the development of the density wave theory in the 1970s.

Keywords: galaxies, rotation, V.M. Slipher, Edwin Hubble, Bertil Lindblad

1 INTRODUCTION

In the middle of the nineteenth century the drawings made by William Parsons, 3rd Earl of Rosse (Parsons, 1926), showed that among the nebulae there was a particular group that he called spiral nebulae. Before 1912, those images of the spiral nebulae and the first photographs by I. Roberts and J.E. Keeler encouraged astronomers to interpret their appearance as the consequence of rotational motion. The English astronomer and photographer, Isaac Roberts (1829–1904) was the first to 'observe' an apparent rotation when he compared two successive photographic plates of the same nebula. Nevertheless he soon came to recognize that this visualization did not justify deducing any rotation (Turner, 1900).

The proper motions of the spiral nebulae were also questioned by Adriaan van Maanen (1884–1946). These issues, which have been studied by many historians of astronomy (e.g. see Berendzen and Hart, 1973; Berendzen, Hart, and Seeley, 1976; Brashear and Hetherington, 1991; Crowe, 1994; Fernie, 1970; Hetherington, 1971, 1972; Smith, 1982, 2008), are well known and they will not be discussed in detail in this paper.

The question of rotation of this particular kind of nebula, the 'spirals', involves rotational velocity and motion of the spiral arms, and observation of the latter requires a careful orientation of the nebula in the line of sight. A controversy took place between V.M. Slipher (1875–1969), Edwin Hubble (1889–1953) and Bertil Lindblad (1882–1965) in the 1930s (see Oort, 1966). This purely observational discussion was important because of its consequences on the hypothesis concerning the dynamics of the spiral arms in what are now called galaxies. The debate on the position of the spiral and elliptical nebulae in relation to our Galaxy was closed by the successful measurements of their distances by Hubble in 1924 (Berendzen and Hoskin, 1971).

Much has been written about Slipher's measurements of radial velocities but little about this controversy. It was only discovered when we were studying the archives¹ at the Lowell Observatory and, more specifically, the letters that were exchanged between Slipher and Hubble.

Vesto Melvin Slipher (but always known simply as

V.M. Slipher), was an astronomer educated at Indiana University at Bloomington (for biographical details see Hart and Berendzen, 1970; Hoyt, 1980). As a favour to Wilbur Cogshall (one of Slipher's teachers), Percival Lowell (1855–1916)² recruited Slipher for the Lowell Observatory, and he arrived in Flagstaff in August 1901. All his research would be devoted to spectroscopy. After working on planets and stars, he obtained his first nebular spectrum of Messier 31 in November 1910 (Slipher, 1910). He soon discovered that this object had a high velocity in the line of sight (Slipher, 1912), and he announced this result to William Wallace Campbell (1862–1938), Director of the Lick Observatory, and then published it (Slipher, 1913a, 1913b).

2 THE DISCOVERY OF SPIRAL ROTATION

After generating the spectra of spiral nebulae, Slipher realized very quickly—by 1912—that the lines were inclined. He had already encountered this phenomenon when he had studied the planets using spectroscopy to measure their velocities of rotation. In a manuscript he wrote:

... the lines of the spectrograms of the Virgo nebula NGC 4594 are inclined. The inclination recalls that shown by a spectrogram of Jupiter made with the spectrographic slit on the equatorial diameter. (Slipher 1914b).³

Thus, it was quite natural for him to apply the same method to determine the velocities of rotation of the spirals. While he initiated this approach in 1912 using a spectrum of the Andromeda Nebula, his study of the rotation of nebulae started in earnest with NGC 4594. In April 1913 he noted: "By its inclined lines this plate furnished direct evidence that nebulae rotate ...", and he went on to offer a systematic analysis of the phenomenon based on many spectral lines for each spiral (Slipher, 1913c).

2.1 Technical Aspects

Slipher's observations for the study of nebulae were made using a 24-inch refractor with a single prism spectrograph (Figure 1). A typed manuscript, copiously annotated by hand, details the problems that he encountered as well as the solutions he found (Slipher, n.d.(b)). While this paper is not dated, we know that it

was written after January 1916 since it includes data obtained at the end of 1915. This interesting paper was never published.

Slipher carried out several experiments between 12 January and 7 October 1915 to determine the optimal instrumental configuration for recording the spectra. From these experiments, he concluded that the best results were obtained using the single prism spectrograph, except in the case of the most luminous nebulae where two prisms gave a better dispersion (Slipher, n.d.(a)). The iron-vanadium spectrum was used for comparison (Figure 2).

The method used to generate the spectrum for the study of nebular rotation consisted of placing the slit along the large axis of a tilted spiral. With this configuration, the central part of the nebula showed a shift corresponding to the radial speed of the nebula as a whole. Furthermore, the part that moved away in the line of sight showed a redshift relative to the center of the nebula, while the part that approached the observer exhibited a relative blueshift. Slipher described his method of data reduction for determining the rotation of the planets in two papers published in 1903 and 1904. The inclination of the lines was measured using a Hartmann microscope.

2.2 Results

In his presentation at the 17th Meeting of the American Astronomical Association (henceforth AAS) at Evanston in late August 1914, Slipher (1914b) indicated that, for NGC 4594 (located in Virgo), the slope was of approximately four degrees and that it corresponded to a circular speed of approximately 100 km/s, at 20" from the centre of the nebula. A note drawn from his working papers illustrates this discovery:

... and as the lines appeared inclined a third spectrogram was made in 1913. While it did not, unfortunately, receive the exposure intended, it nevertheless completely verified the earlier ones both as regards the exceptional displacement and the inclination of the nuclear lines. (Slipher, 1913d).

The first publication on nebular rotation in the *Lowell Observatory Bulletin* (Slipher, 1914a) carries the date of May 1914. In this short article Slipher concluded from his study of NGC 4594 that the nebula rotated and he noted that although most observers, starting with Laplace, had thought that nebulae rotated, it was the first time that this phenomenon had been verified.⁴ The following month, a similar paper was published in *Scientific American*, and Slipher (1914c) was enthusiastic: "If Laplace could have seen this nebula as it really is, he might have found in it a satisfactory illustration of his nebular hypothesis." In addition, Slipher believed that this discovery introduced an excellent method for studying stellar and nebular evolution within the framework of the theory of a protostellar nebula similar to that worked out for the Solar System.

Starting at the end of 1915, Slipher entered into discussion with Campbell over the rotation of spiral nebulae, a question that interested the Director of the Lick Observatory. In a letter dated 4 December 1915, Slipher (1915a) told Campbell that he had obtained plates of the Andromeda Nebula showing rotation and that other studies in progress confirmed this phenom-

enon. He also posed the problem of determining which edge was nearer to the observer because the spiral rotation trajectory depended on the location of this edge.⁵ In his reply, Campbell (1915) did not provide an answer to these questions, but instead urged Slipher to publish this work without delay. Instead, the 19th Meeting of the AAS, held in Swarthmore in September 1915, provided the opportunity for Slipher to present his results.

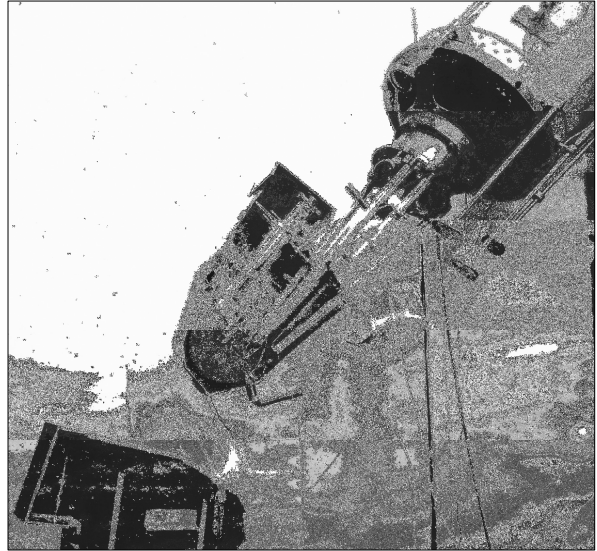


Figure 1: The 24-inch telescope and Slipher's spectrograph (courtesy: Lowell Observatory).

In his working papers, Slipher (1915b) noted the increasing number of photographs of spectra, with analyses that he found encouraging:

... additional cases of rotating nebulae have been met with in the and. Neb.[,] M65, M66 and less incidentally in still other cases. The form of the spectral lines of the andromeda nebula in particular denotes a greater irregular velocity near the nucleus than further ant., but measures for these are difficult and not precise enough to express the motion quantitatively. This type of rotation or internal motion promises to be more common than the planetary disk line rotation shown by the Virgo nebula 4594.

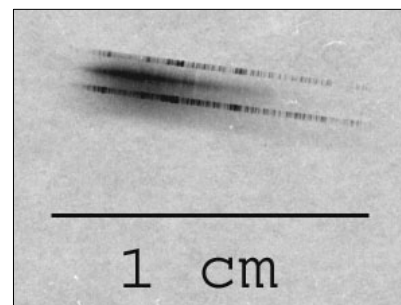


Figure 2: A spectrum of the Andromeda Nebula with the comparison spectra (courtesy: Lowell Observatory).

In 1917 Slipher observed the rotation of six spirals: NGC 224, 2683, 3623, 3627, 4594 and 5005. In December of that year he published new results for NGC 1068 (M77), which according to his calculations rotated at a velocity of 300 km/s 1' from the centre (Slipher, 1917c). In 1921, his paper presented at the 25th Meeting of the AAS included observations of rotation of NGC 221, 224, 1068, 2683, 3623, and 4594. In all six he found "The direction is that in

which the arbor of a spiral spring turns when the spring is being wound up.” (Slipher, 1921). Despite the growing number of spirals he had observed, Slipher (n.d.(b); 1915d) only had velocity measurements for three of these: NGC 224 (Messier 31), NGC 1068 (Messier 77) and NGC 4594 (which are the ones with the highest surface brightness, and probably the most easily-measurable spectra).



Figure 3: The edge-on galaxy NGC 4565 in Coma (courtesy: Bruce Hugo and Leslie Gaul, Adam Block, NOAO, AURA, NFS).

These observations were verified by Francis Pease (1881–1938), an astronomer at the Mount Wilson Observatory with an interest in the rotation of spiral nebulae (Adams, 1938). Slipher found out about Pease’s interest in July 1916 through his correspondence with John Duncan (1882–1962), and took it as a confirmation of the interest of his recent spectral discoveries (Duncan 1916). After 80 hours of exposure, Pease obtained a spectrum for NGC 4594 that enabled him to calculate a rotation velocity of 330 km/s at 2’ from the centre, and he proceeded to publish his results (Pease, 1916). Based on twelve measurements, Pease determined that there was a linear relation between the velocity (V_{rot}) and the distance from the centre of the nebula (r):

$$V_{\text{rot}} = 2.78r + 1180 \quad (1)$$

where V_{rot} is in km/s and r in seconds of arc. The radial velocity of the spiral at the centre (i.e. 0 second of arc) is 1180 km/s.

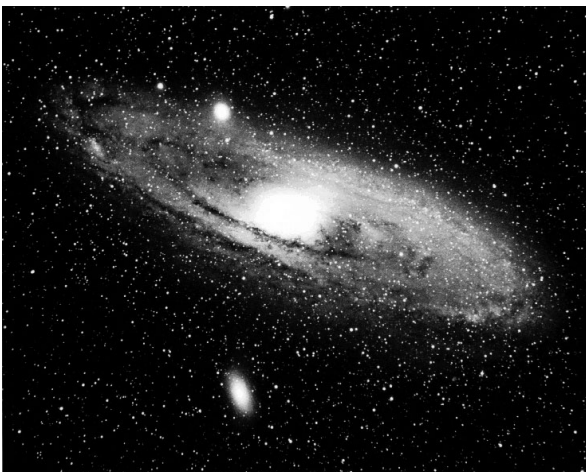


Figure 4: Photograph of the Great Andromeda Nebula (Messier 31) with its dark bands (courtesy and copyright: Jason Ware).

In his data reduction methods, Pease took into account the tilt of the spiral in the plane of the sky. The determination of this linear relation raised several questions. It was clear, for example, that the nebula could not be a solid body in rotation because no such body could possibly be stable at such high speeds. Pease considered the possibility of some (unknown) law that would give a linear velocity-distance relation. Furthermore, the relation made the presence of planets around the centre of the nebula impossible because the linear velocity of such objects would increase as they become closer to the centre (just like the planets of the Solar System), leading to impossibly high velocities.

A little later, Pease (1918) made the same study of Messier 31 and found a velocity of 58 km/s at 2’ from the centre and a similar linear relation:

$$V_{\text{rot}} = -0.48r - 316 \quad (2)$$

The observations made by Slipher (n.d.(b)) led him to a different result: “Angular velocity of Andromeda apparently decreases outward. Linear velocity one minute from nucleus estimated 50 miles.” Applying Pease’s formula would give a velocity of 30 km/s whereas Slipher determined it to be 80 km/s. The inaccuracy of the measurements of rotational velocity can probably explain the difference,⁶ and in this context it is important to note that all these measurements—of Pease and Slipher—only relate to the central part of the core and not to the spiral arms of the Nebula. For example, the measurements made by Pease on NGC 4594 (The Sombrero Galaxy) involved “... approximately the central half of the nebula ...” (Pease, 1916) and in Messier 31 it reached 2.5’.⁷ In 1939, Horace Babcock (1912–2003), with the same method, published results of the same order of magnitude as those of Slipher and Pease for the Andromeda Nebula with a velocity at 2.5’ of 100 km/s, instead of 70 km/s with Pease’s formula (see Babcock, 1939).

These measurements were then combined with the proper motions measured by van Maanen, assuming that the spirals seen edgewise and those seen front-view had the same velocities, and Pease (1916) derived a parallax of 0.00013” (7,700 parsecs) for NGC 4594.

The reception of these results by other astronomers was excellent. One of the most prominent astronomers of that time, W.W. Campbell, wrote to Slipher in 1914: “The rotation observed in NGC 4594 is especially interesting and important ... I hope you will be able to get additional observations of the same kind.” He often used Slipher’s data in his lectures, such as those to the National Academy of Sciences (ibid). As we will see further on, Heber D. Curtis (1872–1942)⁸ was also highly favourable to the rotation theory and wrote that he always preferred Slipher’s views to those of van Maanen. However, in his 1919 review, “On the existence of external galaxies”, Harlow Shapley did not even mention the papers by Slipher or Pease. All his discussion on rotation velocities was based on van Maanen’s publications on Messier 101, and it is only twenty-four years later, in his book, *Galaxies*, that he briefly acknowledged the importance of “... spectroscopically determined rotation ...” (Shapley, 1943: 118).

Although the rotation of the spiral nebulae had been established, the question of the direction of rotation remained open. As we have already noted, to make this determination it is necessary to know which side of the nebula is nearer to the observer.

3 THE CONTROVERSY

3.1 Slipher's Reasoning

As was the case for all his research, Slipher (1915c) communicated his discovery to John Miller (1859–1946), one of his teachers from his university years, and asked his opinion:

If we knew which edge of the nebula is toward us then from the inclination of the lines we could say which way they are turning with reference to the curvature of the branches of the spiral. To get that by parallax measures seems now impossible.

Slipher (*ibid.*) proposed an hypothesis that could extricate him from this situation:

We know that for the great majority of the spindle-edge-on spirals there is a dark lane on their long diameter obviously due to absorbing or occulting material on the nearer edge of the nebula. Imagine we are looking at the great dark-lane spindle of Coma [NGC 4565; see Figure 3 here], and while we are looking we are rising out of its plane. As we pass out of the shadow of the absorbing material, the dark lane will lose intensity and prominence¹³ and the spiral branches begin to show themselves and the dark lane remains only as darker rifts between the arms of the spirals on one side of the nucleus. If we stopped when about 25° above the plane our view of this spindle, it is imaginable that then this nebula might resemble the great Andromeda spiral [see Figure 4], which has much more intense rifts between the spiral arms on one than on the other side. In short, I assume that edge of a spiral which has the darker rifts is the edge nearer to us.

One hypothesis proposed by Pease (1916) was that the dark streak in NGC 4594 could be the "... unilluminated edge of the thin disk surrounding the brilliant nucleus." This opinion was also advocated by Slipher (1917b), who reasoned that the dark lane would seem less dark and prominent if looked at from an upper position.

Based on these assumptions, Slipher (1915c) reached the conclusion that "... the Andromeda nebula is turning into the spiral arms i.e. in the direction we turn a spool to wind the thread onto it." To test this hypothesis, he searched for a sufficient number of spirals with the appropriate characteristics. These studies proved long and difficult, but despite numerous problems, the three or four cases he was able to exploit seemed to agree with his winding-up theory. While Miller expressed his interest in Slipher's discovery, he, like Campbell before him, voiced no opinion on the question of the orientation of the nebular rotation (see Miller, 1915).

At the 25th Meeting of the AAS at the end of December 1920, Slipher presented his latest conclusions concerning the rotation of spiral nebulae. They were based on his measurements of rotation linked to an indicator of the spiral's orientation, which in turn allowed him to determine the direction of the movement:

Considering then that side of the inclined spiral having the darker rifts and deficient illumination to be the one

nearer us, we can interpret the direction of the rotation, shown by the spectrograph, relative to the curvature of the spiral arms where arms are recognizable. In every case the spectrographic results were got independently of any knowledge as to the nearer edge of the spiral and the location of the spiral arms, and likewise these data as to orientation were determined quite independently of the rotation shown by the spectrograph. (Slipher, 1921).

The six nebulae discussed all agreed in showing rotation in the same direction relative to the spiral arms. The direction was that in which the arbor of a spiral spring turned when the spring was being wound up.

A copy of Slipher's (1917b) synthesis of this work preserved at the Lowell Observatory archives contains a typed note from him (Slipher, 1917a). It tells us that, thanks to Walter S. Adams, he had been able to examine an excellent picture of NGC 4594 taken at Mount Wilson Observatory, which revealed fine spiral arms (see Figure 5). This plate allowed him to validate his assumption concerning the rotation of this nebula, but in that case he deduced that the spiral was expanding:

With Professor Adams, I have examined an excellent Mount Wilson photograph of this nebula, which reveals faintly the spiral arms. The shape of the arms allows my spectrographic rotation of the nebula to be interpreted as to direction. It comes out that the object is rotating in the same sense relative to the curvature of the spiral arms as the above discussed spirals were found to be turning.

It thus is reasonably certain that we can generally decide (in the manner described above) from the appearance of spiral nebulae which edge of the nebula is the nearer to us. Hence it follows that the unsymmetrical aspect of the two edges of a spiral is chiefly dependant upon the direction from which we view the nebula. And this, in turn, has its bearing upon the question of the physical nature and the illumination of the spirals in general. (Slipher, 1917a).

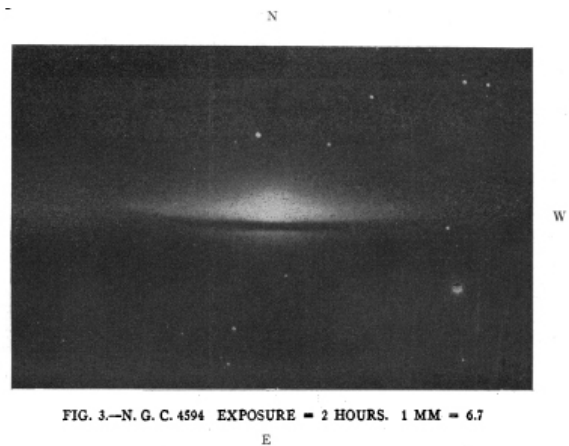


Figure 5: NGC 4594 with dark band and fine spiral arms (after Pease, 1916).

From the high velocity measured for this Nebula, Slipher deduced that some spirals were expanding and matter was being thrown out by the rotation. We must remember that at this time one hypothesis about spiral nebulae was that they were Solar Systems in formation, the central bulge being a new star surrounded by condensed matter.⁹ Instead, Slipher thought about spirals as objects which were expanding, and he called the former hypothesis an old one:

The high velocity of rotation argues that in some cases, at least, - as NGC 4594, for instance - the nebula is, in consequence of rotation, expanding. Indeed the disk-form and the spiral arms of these nebulae imply action, past or present, of expansive forces. The evidence from these observations, and from other sources, to my mind, makes clear the need of our entertaining the view that systems exist which are undergoing expansion. The old theory of condensation of nebulae into stars is today insufficient because one-sided and hence should share the field with the view of the expansion of denser systems into more tenuous ones. In a universe so vast in space and time, its components must be variously circumstanced and it is hardly to be thought that the different forces with expansive tendencies will always be overpowered by those with condensing tendencies. (Slipher, 1917a).

Thus, Slipher (1921), in light of his work on NGC 4594 and with his proposed orientation of the spiral, concluded that for all the spirals he had studied the arms turned like "... a winding spring ... [or a] reel on which one rolls up a wire."

In 1924, Curtis wrote to Slipher in connection with the IAU Commission on Nebulae and took the opportunity to express his own point of view on the rotation of the spirals:

Your results are uniformly to the effect that the motion is in the "direction of the arbor of a spiral spring when it is wound up". Similarly, Pease on the Andromeda nebula, states, "Whether the motion of the nebula is inward or outward along the arms of the spiral depends upon the inclination of the nebula." Referring to his diagram, we find, if we assume as you did in your work that if the "lane" side of the nebula is the nearer, its direction of motion is that found by you. Van Maanen's motions are prevailing outward along the arms of the spiral. Whereas, if the "lane" side is the nearer to us, it seems to me that the spectrographic results directly contradict those secured by van Maanen. Further, I can see no way in reason to put the "lane" side anywhere than on the side toward us. I have never been able to accept VM's results; my feeling is a mixed one of admiration for careful and honest measures on the most difficult subjects, of "watchful waiting" for additional evidence on "being on the fence" and from Missouri, and some measure of total disbelief that the motions he found exist at all in the quantities he gives. One thing that bolsters my attitude with regard to accepting his measures has been what seemed to me the absolute contradiction in the direction of motion given by the spectrographic results, which, per se, appear to me to be worthy of far more confidence.

Curtis' position was confirmed later on, in 1926, in correspondence with Slipher.

In these two letters, Curtis considered that what was contradictory between van Maanen's observations, on the one hand, and those of Slipher and Pease on the other, was the direction of the motion of the spiral arms. For van Maanen, the spirals seemed to unwind, while for Slipher they were winding up. Curtis could not see how to interpret the position of the dark lanes differently from Slipher, and for this reason he was obliged to accept his demonstration. As for the velocities, it was possible to admit that they could be in accord if it was assumed that the distance of the spiral was not more than 35,000 light-years. By the time Curtis wrote his 1926 letter Hubble had measured distances to three spiral nebulae (i.e. NGC 6822, M31 and M33) and shown that each was much farther away

than 35,000 light-years (which definitely contradicted van Maanen's hypothesis), but Curtis did not mention this fact in his letter.

3.2 A Different Point of View from Bertil Lindblad

Bertil Lindblad was a Swedish astronomer and a graduate of Uppsala University (see Öhman, 1970; Oort, 1966). He began his studies on galactic rotation in 1925 with the paper "Star-streaming and the structure of the stellar system", and never stopped them until his death in June 1965. Lindblad was the Director of the Stockholm Observatory from 1927 to 1965, and he spent two years (1920-1922) in the United States, at Lick Observatory and at Mount Wilson.

From his work on Messier 31, Lindblad concluded that its orientation was the opposite of that proposed by Slipher. In 1946 Lindblad published a paper in the *Astrophysical Journal* with his assistant, Rolfe Brahmé (Lindblad and Brahmé, 1946), where he outlined his observations and assumptions. Here he addressed the question of the bands that darken certain parts of the spiral arms, suggesting that the matter responsible for these dark bands was located in both their convex and their concave parts. He based this argument on the face-on spiral, Messier 51, which also presented dark zones in the concave part of the arms. Lindblad concluded that matter was homogeneously distributed throughout the arms, and he suggested that if an observer were to move away from the plane of the spiral, the most distant dark zones would be more apparent than the closer ones. This reasoning led him to the conclusion that "... the part of the nebula which shows heavy obscuration is in all probability farther from us ...", and then he logically deduced the result that "... the direction of rotation found by Slipher and by Pease will be the direction in which the spiral arms wind outward, in accordance with our theoretical rule." In this paper (ibid.), Lindblad also confirmed his earlier conclusion that "... the spiral arms open up in the direction of rotation ..."

Thus Lindblad's position concerning the rotation of these spiral nebulae was the opposite of Slipher's. During the same period, Babcock (1939) studied the Andromeda Nebula and confirmed Slipher's point of view, and Erik Holmberg (1908-2000) also positioned himself on this side of the debate (Holmberg, 1939). Edwin Hubble was also interested in the rotation of spiral nebulae, and in order to determine which interpretation should prevail he decided to undertake a new study.

3.3 Hubble's Point of View

In July 1932, Hubble asked Slipher whether he was still interested in this subject, because he believed that there was an "... outstanding need in nebular research." In response, Slipher (1932) sent Hubble his results and later on they exchanged spectrographic plates (see Hubble, 1941a), and discussed the issue of rotation:

Thank you for your letter on the rotation of spirals. I am sending you prints of 3190 and 4594 as you request, and will be very glad to send others if you wish them. The expression "trail their arms" is ambiguous as you point out. I was careful, in the brief paper for the Academy, to use the expression "the arms trail", for the analogy is with the pin-wheel and the direction is that which you stated in your 1917 paper. (ibid.).

Hubble, who had read Lindblad's publications in the *Astrophysical Journal*, considered publishing on the rotation of the spirals, and he asked Slipher to read his manuscript (Hubble, 1941b). In September 1941 Slipher sent him a long answer as well as his notes on the manuscript itself, and Hubble submitted his revised paper to the *Astrophysical Journal*. It was published in the March 1943 issue (Hubble, 1943), and in this paper Hubble cited Slipher's work at length and he discussed Lindblad's alternative assumptions.

After a clear recapitulation of the various aspects of the problem, Hubble presented two methods for determining the orientation of the spirals. When the spiral is observed edge-on and a dark band passes in front of the central core, its orientation is not debatable, and this is the primary criterion for determining the orientation. In less inclined spirals, this dark band is no longer directly in front of the core but, as long as it is *projected* in front of the core, the orientation is also unambiguous. But when the inclination is insufficient for such a projection then its orientation cannot be determined with any certainty. Hubble then turned to a consideration of secondary criterion for determining the orientation, which he took from Slipher. If the observer could move off the plane of the spiral, he would see the band move away and deviate laterally, making the spiral asymmetrical. In this case, the nearer side is the one without a dark band (e.g., see Figure 4). If we consider the observation of a nebula with a quite visible band barring the core edge-on, when the tilt decreases, the dark band should move away from the core just before the spiral arms become visible. However, if there are any interior bands present, they should remain behind the peripheral band. This is what Hubble observed in three nebulae—NGC 4216, 4258 and 4527—which he compared with NGC 3190 where the primary criterion was present. Hubble also offered a critical analysis of the spirals described by Slipher, and concluded that they contained only one indisputable case, that of NGC 2683. Next, he considered the photographic catalogue of the Mount Wilson Observatory. His first table summarized the results for fifteen well-observed nebulae, all of which satisfied the criteria defined by Hubble. In all these cases the rotation of the arms was in the direction described by Slipher. Hubble added another eight more doubtful cases, which all rotated "... trailing their arm." Finally he criticized Lindblad's criterion as being erroneous, arguing that the asymmetrical concentration of globular clusters and novae showed that the darkening matter was distributed asymmetrically in nebulae seen edge-on and not symmetrically as Lindblad had supposed.

But Lindblad was not convinced, as is shown by his 1946 paper (Lindblad and Brahe, 1946). Using photometric and color measurements, he concluded: "The results indicate that the dissolution of a system into spiral structure proceeds in such a way that the arms open up in the direction of rotation."

3.4 Slipher's Reactions

We know about Slipher's reaction to Hubble's arguments thanks to papers that are housed in the archives of the Lowell Observatory. The documents on this topic are gathered together under the rubric of "Working papers" in a folder containing a series of notes on

the question of the rotation of the spirals (see Slipher, 1946a). Another source of information is the series of letters on the subject exchanged between Hubble and Slipher.

Slipher appears to have been a little irritated by Hubble's article, which he believed did not give enough space to his own work on the subject. Indeed, in an undated note, which was probably penned in 1944, Slipher (n.d.(c)) wrote "Hubble has added nothing in the matter." Moreover, he did not agree with Hubble that NGC 3190 constituted "... the first non-ambiguous spiral." (ibid.). Indeed, he believed that there were many spirals among those that he had published presenting sufficient criteria to reliably orientate them in space. He continued his criticism in the following terms: "Hubble seems to call dark lane of slightly inclined spirals a 'new? criterion' which means he did not understand/read the method here formulated 25 years ago..." (ibid.). In fact, Hubble only used the term "new" for the secondary criteria of tilt that were much more detailed in his paper than in Slipher's earlier ones. But, as we have already stated, he did present all of Slipher's results in detail.

In 1944 Slipher published a note in *Science*, where he insisted on the priority of his work (Slipher, 1944). He then went and detailed his argument in a text dated 2 December 1946, probably with the intention of publishing a more complete paper. Two letters to Hubble, one dated 3 December 1946 and the other undated (but probably written in 1947), show that Slipher (1946b; n.d.(d)) wished to develop his point of view in a more detailed article and in particular to argue against Lindblad's proposal, but this article was never published. In spite of these disagreements, the relations between Hubble and Slipher remained excellent, as is clear from their subsequent epistolary exchanges. Slipher possessed excellent human qualities. He was always courteous and gave his results, slides and plates to all those who asked him for them, as is attested by letters from Campbell, Eddington, Pease, Strömberg and others in the Lowell Observatory Archives. Slipher had helped Hubble, whose personal relationships with other astronomers were sometimes difficult (e.g., see Sandage, 2004: 521, 529, and Brashear and Hetherington, 1991: 240), and he tried to honestly present all of his ideas to a young Edwin Hubble who was not well known at that time and not even a member of the IAU Commission on Nebulae (of which Slipher had been President from 1922 to 1928).¹⁰

3.5 How Did the Controversy End?

Lindblad, himself, contributed to the evolution of the spiral dynamics question. He spent a sabbatical period at Mount Wilson and Palomar, where he met Hubble and was able to use detailed photographs of spiral nebulae taken with the largest telescopes in the world. His studies showed (Lindblad, 1963; 1964) that the matter in the centre of a galaxy rotated more quickly than the spiral arms, meaning that the external parts would 'trail'. He also showed that, at a certain distance from the centre, one could observe a co-rotational resonance (known as 'Lindblad resonance') between the stars and the nebula. Finally, Lindblad also introduced the concept of internal and external zones of instability. Later, between 1964 and 1970, Lin and Shu (1964) went on to develop the

density wave theory. At the observational level, the velocity curves of many galaxies have been measured since 1954 thanks to new techniques in radio astronomy, particularly the study of the 21-cm emission line of neutral hydrogen. Today, astronomers consider the direction of rotation of the spiral nebulae to be well established.

4 CONCLUDING REMARKS

From 1930, the rotation of spiral nebulae was an important issue, mainly because of its implications for the theories of the dynamics of these objects. V.M. Slipher's role in the detection of the rotation and in the determination of the direction of motion of the arms in nebulae attracted the interest of some prominent astronomers, including Hubble. But although he had good intuition, made precise observations and derived interesting hypotheses, Slipher's ideas were not widely known. This illustrates one of the major problems with Slipher: he was reluctant to publish, and most of his papers appeared in the *Lowell Observatory Bulletin* or in *Popular Astronomy*. In contrast, Francis Pease published his results in the *Proceeding of the National Academy of Science*, and Hubble's and Bertil Lindblad's papers appeared in the *Astrophysical Journal*. In contrast, the long paper that Slipher planned to write on the rotation of nebulae never appeared, and partly because of this his work was not very well known and was not widely quoted. Nevertheless, his work, and the controversy which resulted from it, stimulated further research on the dynamics of the spiral arms of galaxies.

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6 NOTES

1. The letters are preserved in boxes with one or two folders for each correspondent of V.M. Slipher. They are in alphabetic order. When the letter has no date on it, the year in brackets was given by the context. The *working papers* are classified by subject and by year. This dating was done by W. Hoyt and by A. Beiser.
2. See Putnam (1994) for an account of Percival Lowell and a history of the Lowell Observatory. For more on the Observatory see Slipher (1927) and for a biography of Lowell see Strauss (2001).
3. In this paper we present all the texts as they actually appear in the manuscripts, without any corrections.
4. It is Campbell who, in November 1914, reported to him a similar observation by Wolf: "The rotation observed in NGC 4594 is especially interesting and important. Wolf observed a similar effect in M 81, as reported by Turner in the Oxford Note Book recently. I hope you will be able to get additional observations of the same kind." The printed version was quoted by Slipher (1914d) as "*Gesellschaft 48 Jahrgang p 162*", which actually refers to

Wolf's annual report of 1913, published in 1914 in *Vierteljahrsschrift der Astronomischen Gesellschaft*, 49, 151-163, and specifically to page 162.

5. The image of a winding spring was used by the astronomers at that time. The measurements with the Doppler effect only give information on velocity but it is necessary to find an orientation for the spiral nebula to determine the direction of its arms.
6. Thanks to radio astronomy, we now know that the velocity quickly increases linearly from the centre and then plateaus or decreases slightly after the maximum. This was also noted by Vera Rubin in 1970 from spectroscopy of emission regions (see Rubin and Ford, 1970).
7. The unresolved central part of the nebula was estimated by Hubble (1929) to be $10' \times 30'$.
8. Heber D. Curtis worked at the Lick Observatory until 1920 where he was recruited as Director of the Allegheny Observatory. In 1930 he moved to the University of Michigan. He was involved with Shapley in the 'Great Debate' (see Smith, 1982).
9. Prior to 1917 this was the view of Campbell and Slipher.
10. See the letters exchanged between V.M. Slipher and Edwin Hubble during the period 1922 to 1927, as well as with other participants during the same interval, and manuscripts of Slipher's reports to the IAU in the Lowell Observatory Archives. During his Presidency, Slipher did not succeed in getting the Nebula Commission to accept Hubble's classification of nebulae, which was rejected because of its evolutionary nature. However, Hubble "... also thought that a decision on the exact scheme of classification of the nebulae to be used in the catalogue had better await the completion of the survey ..." (Meeting of the Commission, 1928).

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