Journal of Astronomical History and Heritage, 10(1), 31-48 (2007).

E.E. BARNARD AND THE ECLIPSE OF IAPETUS IN 1889

James Bryan
McDonald Observatory, 1 University Station, C1402, Austin,
Texas 78712-0259, USA
E-mail: bryan@astro.as.utexas.edu

Abstract: On 1-2 November 1889 E.E. Barnard observed Iapetus as it passed through the shadows of Saturn and its ring system. Over 2.6 hours he produced 75 differential visual magnitude estimates of Iapetus relative to Tethys and Enceladus. The resulting light curve demonstrated the C ring's already known translucence, but it also showed something unexpected. As Iapetus crossed the sunlit gap between Saturn's upper atmosphere and the C ring's inner boundary, instead of remaining constant in brightness, the satellite steadily faded. Apparently, it passed through a shadow, but in 1889 nothing was known to exist in this space. Barnard dismissed the effect as unreal. Although he could not have known, his light curve also implied greater density in the C ring than exists today near the B-C ring boundary. What is the significance of his observation? Were Barnard's visual magnitude estimates wrong? Was the inner ring system significantly different in 1889? Did Barnard observe an event that temporarily affected the ring's density in the line of sight? There are no conclusive answers because he observed the eclipse alone and visually. Yet his method of observation and light curve are thought-provoking. What he recorded conforms in certain ways to the presence of spokes on Saturn's rings. Spacecraft have observed spokes only on the B ring, but visual observers as early as 1873 have seen spokes and spoke-like objects in the A, B and C rings. I speculate on the possibility that Barnard observed spoke shadows intermingled with ring shadows on Iapetus in eclipse.

Keywords: Barnard, Saturn, Iapetus, spokes, Lick Observatory

1 INTRODUCTION

Occultations of stars and of spacecrafts' radio signals by Saturn's rings are used to identify the existence and density of thousands of ringlets and plateaus in this huge planetary ring system. However, the technique of observing planetary rings in transmission was not developed in modern times. Saturn's satellite Iapetus has an orbital inclination of almost 15° and an orbital period of about 79.33 days that make possible rare eclipses. On 1-2 November 1889 Iapetus passed through the complicated shadows of the rings (Figure 1) in what was the first predicted opportunity to observe the rings in transmission. In 1889 four men made direct and indirect contributions to the scientific outcome of the eclipse. Edward E. Barnard is remembered for his role as the only person to observe and report upon what he saw. Albert Marth, a Prussian astronomer and mathematician, provided the prediction that enabled Barnard to act. Edward S. Holden, first Director of Lick Observatory, assigned Barnard to the task, made it difficult for him to do the job, and required a less than truthful account of what happened. Finally, James Clerk Maxwell, who had been dead for ten years, may also have been an influence, not by what he had explained of a particulate ring system but by what he had not explained.

Barnard became famous as a pioneer astrophotographer, but he was fundamentally a visual observer who lived during the transitional years of the late nineteenth and early twentieth centuries when photography replaced eyesight as the chief method in observational astronomy (see Sheehan, 1995). At a time when no instrument was superior to the human eye and good judgment to measure magnitudes for stars and objects that looked like stars, Barnard produced respectable visual photometry for Iapetus in eclipse. In evaluating his work, he confined himself to an unremarkable conclusion that ignored strange evidence. Apparently, he saw on Iapetus a shadow of something unknown that originated between the planet and C ring. Further, although he was unaware of it, his data imply density greater than modern optical depths in the outer C ring. I examine influences that affected his observation, modern concepts of Saturn's ring system, modern and historical visual observations of the rings, and the opinions of Barnard's contemporaries of his skill as a planetary observer. I consider the possibility that his estimated magnitudes for Iapetus were affected not only by normal shadows of the inner ring system but also by shadows from transitory ring spokes.

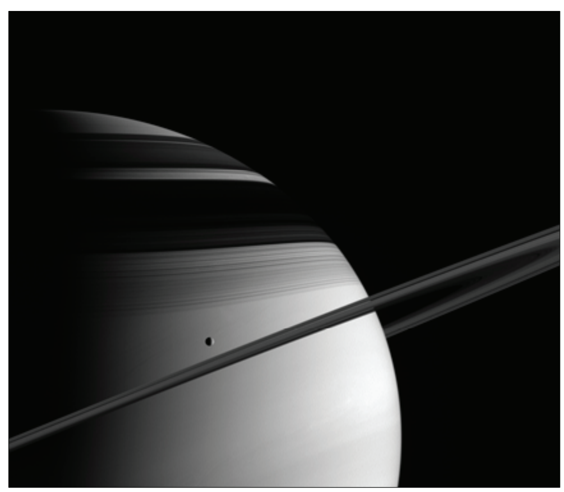

Figure 1: Shadows of Saturn's rings projected upon the planet's northern hemisphere as observed by the Cassini spacecraft from orbit on 10 June 2005. The shadow of the A ring with its narrow, sunlit Encke gap is northernmost, followed southward by the wide, sunlit Cassini division, the very dark B ring shadow, and the tenuous C ring shadow, respectively. Barnard's result for the eclipse of Iapetus implies that normal optical depths in Saturn's inner ring system were different than they are today. What does his observation mean? Tethys, one of the satellites that Barnard used to visually estimate Iapetus' changing brightness in eclipse, appears in the foreground (after NASA/JPL/SSI, 2005b, PIA 07545 with permission from the Cassini Imaging Team, NASA/JPL/SSI).

2 BACKGROUND

The bright supernova, S Andromedae (S And), that appeared in the Andromeda Nebula in August 1885, and Saturn's moon, Iapetus, are very different objects, but for Barnard they were related. In 1885, at age 28 (Figure 2), he had been for two years a student at Vanderbilt University. The 'new star in the Andromeda Nebula' created serious theoretical problems for astronomers. However, Barnard's notebook and published papers make clear that for him the star was strictly an observational matter. Conspicuously absent from his account was a series of visual magnitudes for the supernova. Instead of magnitudes, like many of his contemporaries, Barnard provided picturesque descriptions of its changing brightness. This was a sign of the times, but it also indicated his skill level. In 1885 he did not know how to produce estimated stellar magnitudes according to the best methods available.

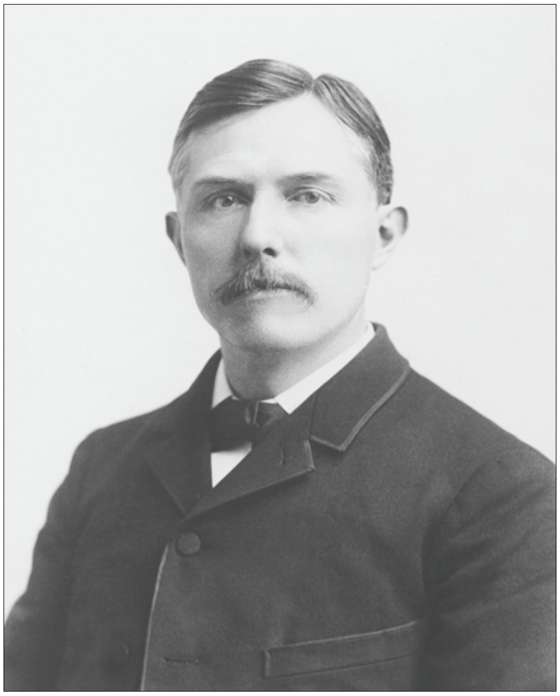

Figure 2: Edward E. Barnard (1857–1923) as photographed in 1885 at age 28. The eclipse of Iapetus was one of several unique observations that Barnard made at Lick Observatory from 1888 to 1895. These secured his reputation as a pre-eminent visual observer (courtesy: Mary Lea Shane Archives of the Lick Observatory, University of California, Santa Cruz).

The most important aspect of Barnard's record of S And was not its contents but who it was that read it. Holden, who awaited his new post as Director at Lick Observatory, read Barnard's earliest report and wrote to him. Knowing what was at stake, Barnard cultivated the contact. In July 1887 he received and accepted Holden's offer of employment as the Junior Astronomer at Lick. Not long after they began working together their relationship deteriorated. Barnard eventually despised Holden. His new job became a source of great scientific opportunity and relentless personal antagonism. He discovered more comets, detected surface markings on Io, and found the expanding shell of Nova Aurigae. His discovery of Jupiter's fifth satellite, Amalthea, was an international sensation. If his approach to S And was not as rigorous as it could have been, at Lick he had an opportunity to improve when he observed the eclipse of Iapetus. His response to the eclipse showed how much he had learned since the supernova about how to deal with stars and objects that look like stars.

Figure 3: James Clerk Maxwell (1831–1879) as photographed in 1855 at age 24 while a Fellow of Trinity College Cambridge. In his Adams Prize Essay for 1856 he demonstrated mathematically that Saturn's rings would remain stable as a system of particles. However, when it came to the collisional environment of a vast number of particles with unknown sizes and shapes, Clerk Maxwell had no mathematics to explain particle motions. He privately speculated that the equatorial region of Saturn might be constantly bombarded by particles that were displaced from their orbits by collisions. By 1889 many, including Barnard, had accepted Clerk Maxwell's hypothesis of particulate rings, but they apparently did not know his equatorial bombardment hypothesis. Barnard disbelieved and ignored his own evidence for activity between the C ring and the planet that he obtained during the eclipse of Iapetus. If he had known Clerk Maxwell's concept of equatorial bombardment, would this have influenced his interpretation? (Courtesy: Master and Fellows of Trinity College, Cambridge).

In the last half of the nineteenth century interest in Saturn was high. Observers saw two obvious bright rings that seemed to change constantly. Evidence was claimed for their rotation, lateral spreading, eccentricity, color differences, and transitory markings (Chambers, 1889). In 1850 a third ring was discovered. It became alternatively known as the gauge, gauze veil, obscure, dark, dusky, crape veil, crape, crepe or C ring between the planet and the B ring. Following his examination of historical observations, Otto W. von Struve (1853) claimed that the ring system's overall width was increasing. He estimated that the inner edge of the C ring was approaching the planet at a rate of about 60 miles annually, and that in about 300 years ring particles would reach the planet (Obituary, 1905). His controversial hypothesis that the ring system was unstable was an influence on selection of a topic for the 1856 Adams Prize Essay at the University of Cambridge. Clerk Maxwell (Brush et al., 1983: 154) (Figure 3) provided the only entry to the competition in that year. In his famous solution for how Saturn's ring system might remain stable, he concluded that

> … the rings must consist of disconnected particles … [being] either solid or liquid, but they must be

> independent [and organized as either] … a series of many concentric rings, each moving with its own velocity, and having its own systems of waves, or else a confused multitude of revolving particles, not arranged in rings, and continually coming into collision with each other.

When Barnard became interested in astronomy in 1876, Clerk Maxwell's work was still not known to or preferred by all astronomers. However, by 1889 it was common knowledge (Brush et al. 1983) so that Barnard (1890) could allude to changes in ring particle density as the obvious explanation of what he had seen during the eclipse.

Barnard could have done nothing with Iapetus without Marth (Figure 4), whose special interest was the orbital motion of planetary satellites. As a manual computer in 1889, he may have consulted *Journal für die reine und angewandte Mathematik* or Crelle's Journal, but references he certainly depended upon were older. Marth (1889d) mentioned use of Urbain-Jean-Joseph Le Verrier's tables for the Sun and planets from 1858, 1861, and 1876. Surprisingly, he still used Alexis Bouvard's tables for Jupiter and Saturn dated 1808 and Bernhard A. von Lindenau's tables for Venus dated 1810 and for Mars dated 1811 (Marth, 1889a). It is no wonder that he routinely published his predictions to encourage observers to supply new information so that he could improve orbital elements. Marth (1889c) offered some sense of his task when he wrote:

> … since my return [to Ireland] I have been hard at work and the cloudiness of the sky has been a favour; but the days are not long enough to allow more than a portion of the work to be got through, which I have laid out for myself.

In the late 1880s Iapetus was one of Marth's projects, and since Holden, who was his long-time correspondent, was in control of the world's largest telescope, Marth (1888) kept him up to date:

> If the ephemeris of Japetus is not too much in error, you may have the very rare opportunity of observing on [1888] Nov. 8 … a close passage of the satellite in the direction of the minor axis of the ring at a distance of only 14" from the centre of Saturn. As the present and the next apparition of the planet are the most favourable for procuring the best observations for determining the orbit of Japetus, I hope it may suit your plans to devote your splendid instrument also to these observations.

He also predicted an eclipse for 1-2 November 1889, and five months in advance encouraged observers with advice that

> … the rare eclipses of Iapetus by the ring-system offer the only chance of deciding several questions … No such observation has ever yet been made … Will Iapetus be visible when Cassini's division … is between the satellite and the Sun? What will be the effect of the shadow of the crape ring upon the appearance of the satellite? Favourably-placed observers will have to answer such questions … and their time will be well spent in doing so. (Marth, 1889b: 427, 429).

The eclipse lasted about 19.1 hours. Iapetus had already passed through the shadow of the rings on the evening or preceding side and was in the planet's shadow when Barnard began to observe not long after Saturn rose at Mt. Hamilton. At Lick Observatory the effect of the Cassini division on Iapetus was not observable, but eclipses by the C ring and part of the B ring on the morning or following side were visible. In his revision of Reverend Thomas W. Webb's *Celestial Objects for Common Telescopes* (1896: 198), Reverend Thomas H.E.C. Espin reported that Barnard observed the event with the 36-inch refractor. That was wrong, but it was an understandable mistake for why should he not have used the great telescope for such an event? While Holden was responsive to Marth's appeal, he did not utilize his 'splendid instrument' for the occasion. Instead, he assigned his Junior Astronomer to do the eclipse with the 12-inch refractor (Figure 5). It was not the greater priority of some competing need, but strife with Holden that kept Barnard from the great telescope that night. Holden had arranged that Barnard should have neither a regularly-assigned night on the 36-inch nor a share of its idle time. Such was their animosity that Barnard refused to make special requests for time. Holden had the 36-inch on the night of the eclipse. Regardless of Marth and Iapetus, he closed early and left for his residence without inviting Barnard to switch telescopes. Later, when the importance of Barnard's result became obvious, Holden instructed his seething subordinate to publish a false explanation as to why the 36-inch was not used (Sheehan, 1995).

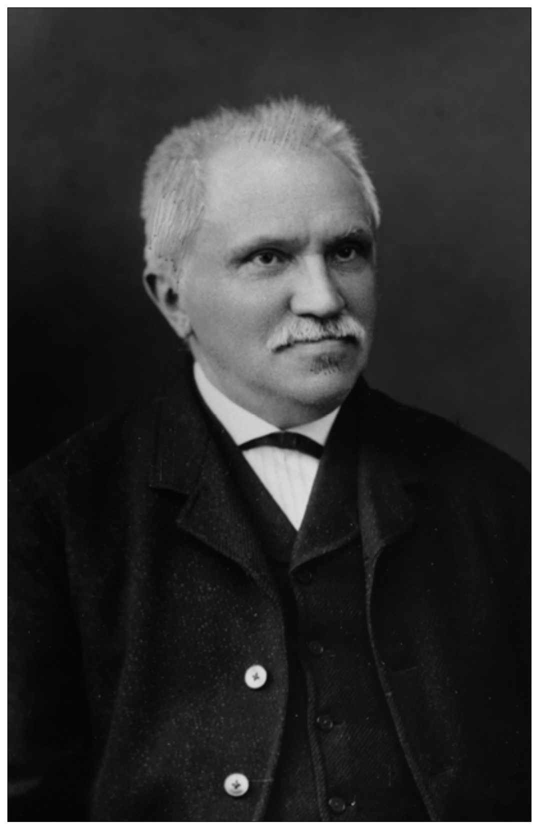

Figure 4: Albert Marth (1828–1897) as photographed in 1885 at age 57. Marth computed the ephemeris for the 1889 eclipse of Iapetus and encouraged others to observe it. Only Barnard observed the eclipse and published results (courtesy: Royal Astronomical Society).

After Marth's death in 1897, Edward B. Knobel (Obituary, 1898: 141) urged that " ... he well earned the gratitude of astronomers for the tables and ephemerides he regularly prepared for so many years for observations of the satellites ..." However, it was Marth (1890) who sent thanks to Holden regarding the eclipse of Iapetus:

> I am much obliged to you for having kindly sent me No 5 of the Publications of your new Astron. Soc. [of the Pacific], so that I have learnt how successful Prof. Barnard has been in observing the reappearance of Japetus and that the prediction has not been made in vain.

Holden would have been courteous and possibly grateful as well, but he would not have revealed to Marth the extent to which his indifference or bungling affected the event.

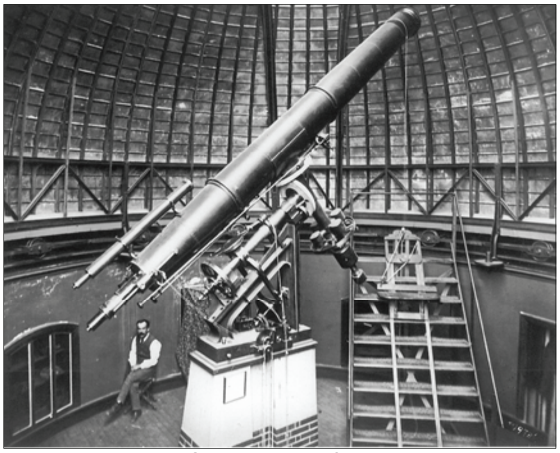

Figure 5: The Alvan Clark 12-inch refractor that Barnard used to observe the eclipse of Iapetus in 1889. It was installed in 1881 and remained in service until 1979 when it was removed in favor of the Anna Nickel 40-inch reflector. The 12-inch is stored on Mt. Hamilton (courtesy: Mary Lea Shane Archives of the Lick Observatory, University of California, Santa Cruz).

3 BARNARD'S METHOD

Not long after Saturn rose, Barnard found that Iapetus was still eclipsed by the planet. He described its reappearance:

> At 5h 25m sidereal time the satellite was faintly caught [as it emerged from the planet's shadow], and for at least one half minute before this it was seen, but so faint and uncertain that it was not recorded. At the above time it was about as bright as Enceladus. Its light increased pretty rapidly. The point of appearance formed a right-angled triangle with Tethys and Enceladus …
>
> The idea at once occurred that it would be an excellent plan to test the effect of the shadow of the crape ring on the visibility of the satellite, by frequent comparisons of the light of Iapetus with that of Tethys and Enceladus. A series of comparisons was therefore begun. The standard of comparison was the difference of brightness between Tethys and Enceladus—this quantity being mentally divided into ten equal parts. (Barnard, 1890: 107).

To divide into ten parts the difference in light intensity between Tethys and Enceladus resembles Edward C. Pickering's (1882) step-estimation process. This was a variant of Friedrich Argelander's (1844) method that was intended for use with variable stars. According to Seth C. Chandler, Jr. (1885: 247), "… Argelander's method of observation has proved, in precision, convenience, and fruitfulness, superior to any photometric apparatus yet devised." Barnard's record for S And makes clear that he did not know either form of step estimation in 1885. If he did not learn it independently, someone on Mt. Hamilton probably taught it to him. The most likely teacher was his friend Sherburne W. Burnham who had been a participant on the international Committee on Standards of Stellar Magnitudes. The Committee intended to produce a system of standard stars to reduce confusion created by multiple, competing magnitude scales (Pickering et al., 1881). Since Burnham (1889) used Argelander's stellar magnitude scale and was involved with Pickering's Committee, it is likely that he knew at least one form of step estimation. Holden was also on the Committee, but it seems unlikely that Barnard would have learned the technique from him. Regardless of how he learned it, 69 years after the eclipse of Iapetus, Allan Cook and Frederick Franklin (1958: 378) wrote that Barnard's magnitude estimates for Iapetus in eclipse were still "… probably the best transmission data concerning the optical thickness of both rings B and C."

Barnard's plan was simple. He intended to compare the changing illumination of Iapetus to unchanging Tethys and Enceladus. The surfaces of these icy worlds are active. Saturn's satellites emit dust into and collect it from the space in which they orbit. In particular, Enceladus is a spectacular emitter of water ice particles that probably compose the E ring (Spahn et al., 2006, NASA/JPL/SSI, 2006a). The photometric characteristics of these bodies are complex. Except for one fact, their environments were unknown in 1889. Iapetus has bright and dark hemispheres that cause its apparent magnitude to change significantly with orbital phase. By comparison, changes in the magnitudes of Tethys and Enceladus are subtle. The short time in which Barnard observed made his method practical.

Pickering (1879) found that Tethys and Enceladus differed by 0.94 magnitude, but Barnard (1890), with no standard stars and only instinct to guide him, correctly believed that the difference was greater. The three satellites each display one hemisphere to Saturn. Further, all three have non-uniform albedos, particularly Iapetus. Consequently, solar phase angle (α), orbital phase angle (θ) and sub-observer latitude control orbital cyclic changes in their apparent magnitudes. Solar phase is the angle subtended at Saturn by the Sun and Earth. The maximum value is about 6.3º, which occurs at quadrature. Barnard observed near 5.9º. Orbital phase is the angular distance of a satellite from geocentric superior conjunction (GSC) or the point at which the satellite is on the far side of Saturn, 180º from Earth. An orbital phase angle of 270° is western elongation. Iapetus reached GSC on 2.80 November 1889 (U.S. Naval Observatory, 1886: 479). Barnard observed a little more than one day before GSC so that Iapetus' orbital phase angle should have been about 355º. Tethys was approaching western elongation with perhaps $250º \leq \theta \leq 260º$. Enceladus was trailing at about $220º \leq \theta \leq 240º$. The sub-observer latitude was in the southern hemispheres of both Tethys and Enceladus. Anne Verbiscer (pers. comm., 2005) used the Hubble Space Telescope to observe the satellites at southerly sub-observer latitudes. With $\alpha = 6.014º$, she found for Enceladus V = 11.807 ± 0.006 and 11.844 ± 0.006 at respective orbital longitudes of 289.70º and 303.38º. With $\alpha = 6.258º$, she found for Tethys V = 10.418 ± 0.003 at orbital longitude 177.00º, and estimated that the satellite would be 0.05 magnitude fainter at greatest western elongation. I adopt a difference between the two satellites of 1.4 ± 0.1 magnitudes.

According to William Gray (pers. comm., 2005), Saturn was about magnitude 1, and the major axis of the rings was about 37.5 arc seconds. Barnard (1889a) observed the entire event at a magnification of 150× in an actual field of view of about 16 arc minutes. He found Iapetus, Tethys, and Enceladus to be closely arranged in a triangle with sides of 13, 17, and 19 arc seconds. Enceladus was about 6 arc seconds from the outer edge of the rings. A modern ephemeris shows the triangle of satellites with sides of 11, 22, and 23 arc seconds with Enceladus at about 13 arc seconds from the rings (Gray, pers. comm., 2005). Motion by Tethys and Enceladus, with orbital periods of 1.888 and 1.370 days, respectively, could have noticeably rearranged the triangle. However, both satellites were approaching western elongation so that both had diminished angular movement on the sky. Iapetus' orbital period of about 79.33 days made its apparent motion slow.

Barnard (1890, 1889a) presented his observations in a table with an accompanying light curve (Figure 6), but selected entries from his notebook give a better sense of his experience at the telescope:

5h 25m	K = Japetus = F [,] faint at sid[ereal] 5h 25m [,] saw it probably 1m earlier v. faint [a second note] at sid 5h 25m Japetus = F = Enceladus
5 29	a little brighter than F say 2/10 the dist[ance]
5 30	nearer br[ightness] of C than F[;] = 7/10 ±
5 35	K is 8/10 from F to C in brightness …
7 50	= 0/10 or perhaps a little less than F …
7 56	-3/10 or -4/10 vvf
7 58	-5/10 eef
7 59	-6/10 eeef
8 01	no trace[;] F easy at this time

Letters denote the three satellites: Iapetus (K), Tethys (C), and Enceladus (F). Time is local sidereal time. Fractions give the changing light intensity, e.g. 8/10 means 8 arbitrary steps brighter than Enceladus and 2 arbitrary steps fainter than Tethys while -4/10 means 4 steps fainter than Enceladus and 14 steps fainter than Tethys. The notes also use language that was intended for comets and nebulae. The terms 'vvf', 'eef', and 'eeef' are descriptions of faintness in which 'v' means very and 'e' means extremely.

4 BARNARD'S RESULTS

Barnard (1892: 121) summarized the eclipse as having "… given us more information about the crape ring of Saturn, perhaps, than could possibly have been obtained by a hundred years of ordinary observing." His advantages of natural ability, experience, location, equipment, and the rare opportunity to observe the rings in transmission promised a leap forward. Barnard's (1890: 109) conclusion for the density of the B ring was new information, but his result for the C ring was a model of anticlimax:

> … the crape ring is truly transparent—the sunlight sifting through it. The particles composing it cut off an appreciable quantity of sunlight. They cluster more thickly … as it approaches the bright rings … so far as the penetration of the solar rays is concerned, the bright ring is fully as opaque as the globe of Saturn itself.

In 1852 August William S. Jacob became probably the first person to see the translucent condition of the C ring (Alexander, 1962). However, Etienne L. Trouvelot (1877: 191) thoroughly pre-empted Barnard's conclusion by reporting that

> … the inner portion of the dusky ring disappears in the light of the planet at that part which is projected upon its disk … the dusky ring is not transparent throughout, contrary to all the observations made hitherto; … it grows more dense as it recedes from the planet … at about the middle of its width, the limb of the planet ceases entirely to be seen through it.

Barnard's largely confirmatory result ensured a quiet public reception, but the matter of what he saw and what it meant is not repetitious of others' work. It is also not easily explained.

Ten years before Pioneer 11 arrived at Saturn, Pierre Guérin (1970) announced his photographic discovery of what he called the D ring. It was a tenuous object located between the C ring and the upper atmosphere of the planet. According to Mark Showalter (1996: 677), "… for the remainder of the 1970's, numerous astronomers attempted to confirm the D Ring's existence, with mixed results …" In considering Cook's and Franklin's reliance on Bar-nard, Ignacio Ferrín (1974: 168) ventured "… that these [Barnard's] observations contain evidence of ring D discovered by Guérin …" Ferrín concluded that his own measurements of Guérin's images were "… in excellent agreement with the observations of Barnard … Without suspecting its existence, this ring had been observed by him in 1890."

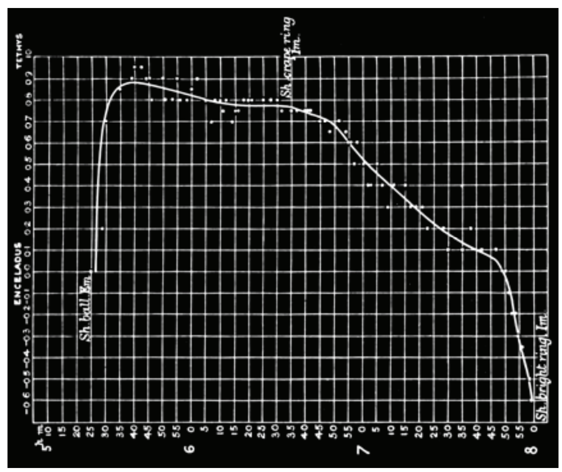

Figure 6: Barnard's light curve for the eclipse of Iapetus. Originally oriented with its text horizontal, his figure is presented here with a vertical magnitude axis according to modern use. Iapetus emerged from the planet's shadow at "Sh[adow] ball Em[ersion]," reached greatest brightness soon thereafter, faded slightly and entered the shadow of the C ring at "Sh.[adow] crape ring Im[mersion]," and disappeared into the shadow of the B ring at "Sh[adow] bright ring Im[mersion]." (Reprinted from "Observations of the eclipse of Iapetus in the shadows of the globe, crape ring, and bright ring of Saturn, 1889 November 1" by E.E. Barnard, *MNRAS*, 50, 107-110, 1890, figure entitled "Light curve of the eclipse of Iapetus …" with permission from Blackwell Publishing.)

However, Barnard did suspect something. He did not suggest that what he saw was real and certainly not that it was a discovery, but he was aware of a situation in his light curve. He could hardly have missed it since 40% of his data defined the effect. The longer he considered the matter, the more certain he became that it meant nothing. On 6 November 1889 he wrote for *Publications of the Astronomical Society of the Pacific* a preliminary account of the eclipse in which he identified an anomaly in the light curve for Iapetus, a decrease of 0.1 magnitude or one-tenth of the difference in brightness between Tethys and Enceladus. Since the two satellites differ by about 1.4 magnitudes, the change he noted was about 0.14 magnitude:

> Japetus required a little over ten minutes to become wholly free from the shadow of the ball. After remaining at its full brightness for fifteen minutes, it began very slowly to decrease in light; however changing less than 0.1 magnitude in forty minutes' time. (Barnard, 1889b: 127).

A month later he sent his first detailed account to *Monthly Notices of the Royal Astronomical Society*. Now he explained away the anomaly:

> I do not understand the slight decrease of light so soon after the maximum had been reached, as it is evident from the curve that the satellite did not experience the effects of the crape ring until 6h 35m. If, however, we consider that the variation of light between 5h 40m and 6h 15m represents only 0.1 of a magnitude, it has less signification … I would rather refer this peculiarity to the fact that the seeing became better, and a fairer estimation could therefore be made of the relative light; if so the curve should be flatter near 5h 35m … (Barnard, 1890: 108-109).

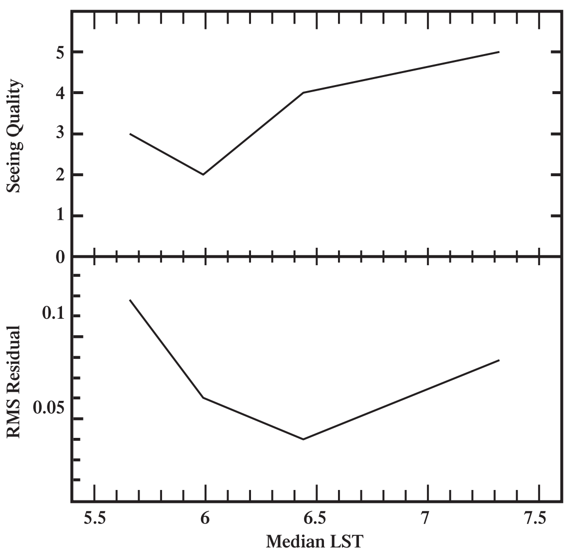

Figure 7: Seeing quality as well as root mean square residual for seeing-related subsets of estimated magnitudes are shown as functions of local sidereal time (LST) during the eclipse of Iapetus. Barnard explained Iapetus' apparent decline in brightness before it entered the C ring shadow as an effect of changes in seeing quality that adversely affected his magnitude estimates. He rated seeing quality on an arbitrary scale in which 1 was worst and 5 was best. During the eclipse Barnard (1889a) noted four episodes in which seeing changed. For the second episode, at the median time of 6 hours LST, I inferred a seeing quality of 2 since he did not assign a rating but wrote only that seeing worsened. Linear or low order polynomial fits to the data in each subset yielded root mean square residuals. Presumably, these residuals describe the accuracy or consistency of Barnard's visual estimation process. If his hypothesis is correct, decline in seeing quality should be correlated with increased residuals. There is no such correlation. Consequently, his accuracy or consistency was not affected by changes in seeing quality. Iapetus' fading trend before the C ring eclipse had another explanation.

In *Astronomy and Astro-Physics*, he treated the situation as meaningless and omitted it entirely:

> Near the predicted time the satellite re-appeared from the shadow of the ball into the sunlight shining between the ball and rings. It quickly assumed its normal light, and after remaining thus for an hour and twenty minutes, it began to fade and so continued for an hour, having during that time entered and passed through the shade of the crape ring. (Barnard, 1892: 121).

In describing seeing, Barnard (1890: 109) explained that it "… ranged from 2 at the first observations of Iapetus up to 5 as dawn appeared …", with worst seeing represented as 1 and best as 5. In his notebook, Barnard (1889a) wrote that at 5h 5m "seeing = 3"; at 5h 51m "seeing getting bad"; at 6h 15m "seeing = 4 for some time"; at 6h 48m "seeing has got v[ery] good"; and at 6h 55.5m and for the duration "seeing = 5." He added that

> … in the last part of the records the seeing = 5—does not mean that it was 5 all along, I waited for steadiness to make an estimate, it fluctuated very much from 1 to 5.

To test his suggestion that accuracy of the magnitude estimates was a function of seeing, I binned Barnard's observations according to time intervals defined by seeing values that he assigned or implied. There were four recorded episodes in which seeing changed during the 2.6-hour event. To the observations in each of these subsets, I fitted linear or polynomial functions that approximated related segments of the light curve. I obtained a root mean square residual for each subset and inferred that a small residual meant more accurate or at least more consistent magnitude estimates. The results appear in Figure 7. Subset 1, in mediocre seeing, had a residual of 0.107. Against Barnard's expectation, the residual decreased to 0.055 when seeing worsened to poor in subset 2. When seeing improved to good in subset 3 the residual fell to 0.033. When seeing became excellent in subset 4, the residual contrarily grew to 0.075. Because seeing quality is not correlated with the residuals, seeing was not a controlling influence on his magnitude estimates. Something else caused Iapetus to fade prior to the C ring eclipse. In 1889 there was an hypothesis to explain what Barnard saw, but few people knew it.

Barnard and others believed that nothing existed in the space between Saturn and the C ring. However, the nineteenth century's master of planetary ring mathematics thought differently. In a letter to William Thomson (later Lord Kelvin), Clerk Maxwell (1857) described a fantastic scene that may reflect Struve's claim for spreading of the ring system:

> What shall we say to a great stratum of rubbish jostling and jumbling round Saturn without hope of rest or agreement in itself till it falls piecemeal and grinds a fiery ring round Saturns equator, leaving a wide tract of lava with dust and blocks … on each side and the western side of every hill battered with hot rocks? … As for the men of Saturn I should recommend them to go by tunnel when they cross the 'line'.

This private expression has no clear counterpart in the published Adams Prize Essay, but it may be related to his statement that

> … when we come to deal with collisions among bodies of unknown number, size, and shape, we can no longer trace the mathematical laws of their motion with any distinctness … whatever catastrophes may be indicated by the various theories we have attempted. (Brush et al., 1983: 136).

By 1889 there had been no new observational evidence that the rings were measurably spreading. Struve was no longer a factor. Clerk Maxwell, however, was very credible. His ring theory was well known, but his bombardment hypothesis was effectively unknown. Given that Barnard believed the particulate ring theory, it is likely that he would have believed, or at least considered, equatorial bombardment, if he had known about it. In that case, he might have interpreted what he saw before the C ring eclipse as Iapetus in the shadow of an unknown—in Clerk Maxwell's words—hailstorm ring (Brush et al., 1983: 48), a source of projectiles for an equatorial catastrophe. Without the bombardment hypothesis, Barnard was alone with an observation that he refused to believe and eventually excluded from the account.

5 THE D RING

When Pioneer 11 reached Saturn in 1979, the wonders it observed did not include Guérin's ring: "The D ring was not seen in any viewing geometry and its existence is doubtful." (Gehrels et al., 1980). In 1980 and 1981, Voyagers 1 and 2 swept through the Saturn system. Their imaging capability was superior to Pioneer's which enabled them to detect "… a faint inner D ring, extending to within 7,000 km of the planet's atmosphere." (Smith et al., 1982: 530). According to Showalter (1996: 677), the ring was "… vastly fainter than previous Earth-based claims…", meaning that it "… could never have been detected from the ground." He identified three narrow ringlets (D68, D72, and D73) and broad, faint, wave-like regions. However, 25 years after Voyager 1, the Cassini spacecraft observed

> … very significant changes in the appearance of the D ring … D72, which was the brightest feature in the D-ring … has decreased in brightness by more than an order of magnitude relative to the other ringlets … [and has] moved inward about 200 km … (NASA/JPL/SSI, 2005a: 1).

Amanda Bosh and Catherine Olkin (1996) used the Hubble Space Telescope to observe the first occultation of a star (GSC5249-01240) by the tenuous D ring. At wavelengths in the range 350-700 nm they found a line-of-sight optical depth of $\tau \cong 0.019$ for the densest part of the ring. From Voyager results Showalter (1996) concluded that D73 had an optical depth normal to the ring plane of $\tau_0 \cong 0.00002$. If the condition of the D ring in the 1980s and 1990s was substantially the same as its state in 1889, what do these observations mean for Barnard?

Bosh and Olkin observed when Saturn's rings had an opening angle of 2.7º. Where zero indicates unobstructed translucence and 1.0 effectively means no transmission of light, their value for the ring's optical depth normal to the ring plane is

$$\tau_0 \cong 0.019 \times \sin(2.7^\circ) \cong 0.0009. \quad (1)$$

Barnard saw an opening angle on the rings of -8.49º (Gray, pers. comm., 2005). If in 1889 the D ring had features with normal optical depths of $\tau_0 = 0.0009$ and 0.00002, Barnard would have encountered optical depths in the line of sight of

$$\tau = 0.0009 / \sin(8.49^\circ) = 0.006 \quad (2)$$

and

$$\tau = 0.00002 / \sin(8.49^\circ) = 0.00014. \quad (3)$$

Line-of-sight optical depth is related to change in magnitude (Δm) by the approximation,

$$\tau = \Delta m / 1.09. \quad (4)$$

In the shadows of such features, Iapetus should have faded by approximately 0.007 and 0.00015 magnitude. This would have been a non-event for Barnard. Yet he recorded a gradual decrease in Iapetus of about 0.14 magnitude in the vicinity of the D ring. An opening angle of -8.49º implies a line-of-sight optical depth of $\tau = 0.13$ and a normal optical depth of $\tau_0 \cong 0.02$, about 20 times what Bosh and Olkin observed and about 1,000 times Showalter's result. The Cassini spacecraft has demonstrated that the D ring changes relatively quickly, but for Barnard to have seen its shadow, the ring needed radically greater density. If it was not dense enough to create a visual effect 117 years ago, another cause must explain what he saw. Observational error is the most obvious possibility.

6 FACTORS THAT AFFECTED BARNARD'S OBSERVATION

Barnard's 'excellent plan' was not easy to accomplish. Interference by light from Saturn, the large difference of 1.4 magnitudes between the standard objects, the smallness of the unanticipated change in Iapetus' brightness prior to the C ring eclipse, a risk of bias due to the short time interval between his observations, and a risk of position angle error in his magnitude estimates were all factors, influences, and possibilities.

Saturn introduced scattered light into the telescopic field, but Barnard neither commented nor complained. His discovery of the fifth satellite of Jupiter gives the best indication of his sense of a faint satellite near a bright planet. He discovered Amalthea (V ≥ 14.1) when he moved the brilliant planet just outside the field. Otherwise, with any part of Jupiter in view, the satellite became invisible. In congratulating Barnard, E. Walter Maunder (1894), at the Royal Observatory (Greenwich), described his own experience:

> I have tried hard again & again to catch a glimpse of your fifth satellite with our new 28 inch telescope, but only succeeded on two occasions in just fancying I saw it for a moment … my ill-success has given me a very high idea of the skill, patience, & keenness of sight which you must possess to have made the original discovery.

Presumably, three years earlier the same skill, patience, and keenness of sight had no trouble with three satellites near Saturn.

The difference of 1.4 magnitudes between Enceladus and Tethys is large for visual magnitude estimation, but it seems not to have been a problem. Barnard divided the intensity difference between Enceladus and Tethys into tenths or 0.14 magnitude units. However, his step—the smallest difference in light intensity he could actually see—was yet smaller. When Barnard detected the inner edge of the C ring, he did so by showing change in Iapetus of 0.07 magnitude. Similar fine changes appear elsewhere in the light curve. Many visual variable star observers have steps of 0.1 magnitude, but the best observers are more sensitive. Two of Barnard's steps describe how Iapetus faded between its maximum brightness and the C-D ring boundary, meaning that the detection was for him somewhat better than marginal. In a related matter, color is an issue for visual magnitude estimation, but

Barnard's response to color may not have been a factor since the three satellites have about the same color. Cox (2000) reported mean color indices in the range 0.70 ≤ B-V ≤ 0.73. For Iapetus in orbital phases 92º ≤ θ ≤ 270º, 0.82 ≤ B-V ≤ 0.69 (Millis, 1977). For Tethys in orbital phases 247º ≤ θ ≤ 327º, 0.63 ≤ B-V ≤ 0.79 (Blair and Owen, 1974). Similar ranges for Enceladus were not available.

He expected to obtain a featureless light curve for Iapetus in the gap between planet and rings as he implied when he wrote, "… the curve should be flatter near 5h 35m, to correspond with that near 6h 25m." (Barnard, 1890: 109). This was an assumption not a fact. His anticipation of events could have been a problem since visual observers are known to see what they believe. Yet, given that he recorded Iapetus' declining light, not its constancy, in 30 estimates before the C ring eclipse, Barnard's objectivity went unharmed. He also observed at a rate of about one estimated magnitude every two minutes. That pace invited other bias because his estimates were not independent. He had no time to forget previous estimates and trends. The C-D ring boundary is a subtle transition that a biased observer might miss. Barnard correctly identified the boundary at 1.235 planetary radii. Regardless of what he anticipated and of what he knew about his own observations, he remained objective.

The arrangement of stars in a field of view can affect a visual observer's sense of their brightness. When two stars of equal brightness and similar color are arranged one above the other, "… the lower will appear the brighter, perhaps by as much as half a magnitude." (Isles and Lewis, 1990: 40-41). The effect is known as position angle error. Barnard probably knew nothing about it. An observer can avoid the problem by arranging pairs of stars horizontally. It is not possible to be certain how Barnard oriented the three satellites. His notes do not discuss this, but his sketch of the scene implies that he kept Iapetus low relative to Tethys and Enceladus throughout the eclipse. When Iapetus arrived at 1.06 planetary radii it reached maximum brightness. "It was then about 0.1 magnitude less than Tethys." (Barnard, 1889b: 127) or about magnitude 10.6. He observed when the solar phase angle was about 5.9º and Iapetus' orbital phase was about 355º. Under similar circumstances, Robert Millis (1973) measured Iapetus to be V ≅ 10.9, corrected to Saturn's mean opposition distance. The difference of 0.3 magnitude may have been position angle error that affected all of his estimates. If so, peak brightness for Barnard's light curve can be set according to Millis.

With the exception of position angle error, Barnard's estimated magnitudes appear to be reasonably correct.

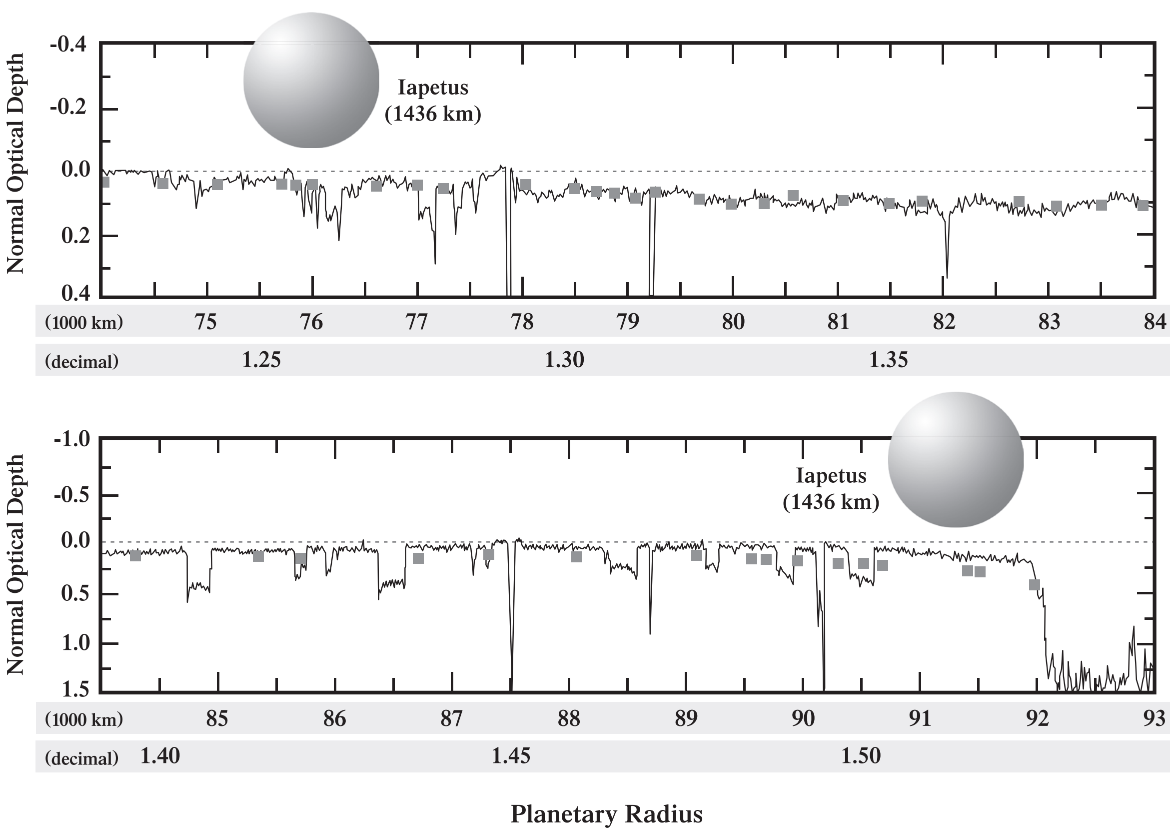

Figure 8: High resolution transmission curve of the C ring. Superimposed upon the modern transmission curve are normal optical depths (solid squares) derived from each of Barnard's visual magnitude estimates of Iapetus in eclipse. Squares indicate the center of Iapetus at the time of each of his observations. In the first half of the C ring eclipse Barnard's results agree with modern values. In the second half, his results are consistently greater than modern values. Uncertainty is about ± 0.02 normal optical depth based on an uncertainty of ± 0.1 magnitude in his estimates. Iapetus was large relative to the C ring's fine ringlets and plateaus which explains why Barnard did not resolve these features. (Transmission curve reprinted with permission of R.G. French and Elsevier from "Geometry of the Saturn system from the 3 July 1989 occultation of 28 Sgr and Voyager observations" by R.G. French et al., *Icarus*, 103, 163-214, 1993, figure 4, "Atlas of ring feature designations," copyright 1993 Elsevier.)

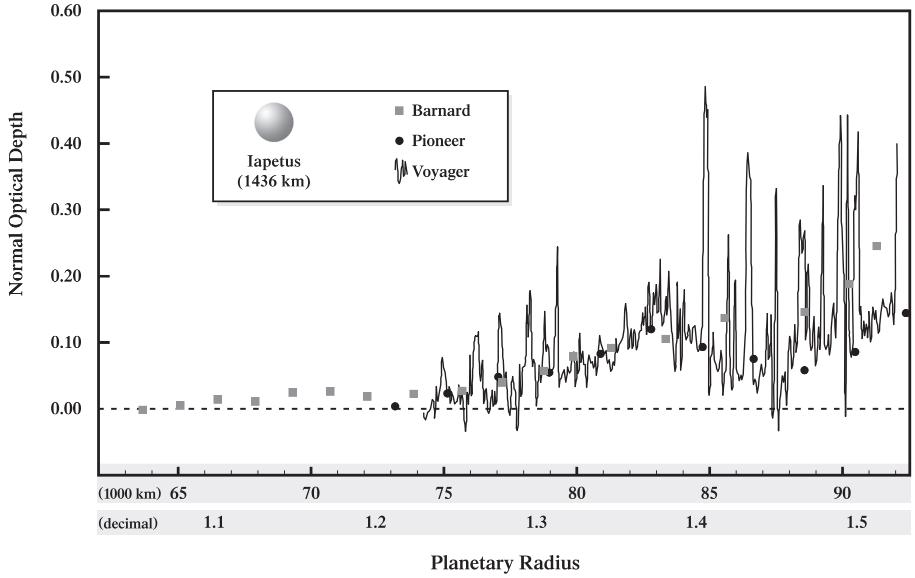

Figure 9: Low resolution transmission curve for the C ring. The plotted curve represents observations by Voyager 2. Filled circles are Pioneer 11 results. Filled squares are means of four normal optical depths as derived from Barnard's visual magnitude estimates of Iapetus in eclipse. Barnard correctly identified the faint C-D ring boundary at 1.235 planetary radii. He also correctly concluded that there is no gap at the B-C ring boundary at 1.525 planetary radii. He agreed with the general trend of modern transmission values in the inner C ring but disagreed in the outer C ring and D ring. Is this disagreement due to observational error or is it evidence for a condition that was not present for Pioneer 11 and Voyager 2? (Transmission curves for Voyager 2 and Pioneer 11 reprinted with permission of B.R. Sandel and Science from "Extreme ultraviolet observations from the Voyager 2 encounter with Saturn" by B.R. Sandel et al., *Science*, 215, 548-553, 1982, figure 4, "Normal optical depths in the C ring determined by the UVS during the delta Sco exit of the rings," copyright 1982 Science.)

7 BARNARD AND THE C RING

It would help to compare Barnard's results with those of other observers, but there are none. There are, however, modern observations of optical depth in the C ring. To compare Barnard's observations to what is known about the C ring today requires the assumption that the visual appearance of the ring has not changed significantly in more than a century. I converted Barnard's visual magnitude differences to differences in V magnitude and further converted these to optical depth in the line of sight and finally to optical depth normal to the plane of Saturn's rings. I plotted his transmission curve with transmission curves from modern sources including Pioneer 11 and Voyagers 1 and 2 as shown in Figures 8 and 9. The uncertainty of Barnard's estimated magnitudes is about ±0.01 while uncertainty of derived normal optical depths is about ±0.02.

Figure 8 plots all of Barnard's optical depths on a transmission curve of the C ring by Richard French et al. (1993) obtained from an occultation of 28 Sgr and the Voyagers. The C ring has wave-like structure that is interrupted by optically deep ringlets and plateaus that are narrower than the diameter of Iapetus. Shadows from all of this fell upon the satellite. Did Barnard resolve structure in the C ring? From 1.488 to 1.502 planetary radii, Iapetus encountered the shadows of two plateaus and a ringlet with widths from 60 to 200 km and normal optical depths from 0.25 to more than 0.50. The -8.49º opening angle on Saturn's rings created line of sight optical depths for these features that were great enough to substantially dim an occulted star, but Barnard saw no effect on Iapetus from this combination of narrow, deep shadows. Presumably, the satellite was too large to be affected.

However, he was able to recognize the C-D ring boundary and the B-C ring boundary. As to the latter, since the 1850s some observers argued that a division existed between the B and C rings (Alexander, 1962). Barnard (1895: 369) gave his opinion:

> No division was seen between the Crape ring and the inner bright ring, as has sometimes been shown on drawings. This supposed division, however, was proved to have no real existence by my observations of the eclipse of Japetus in the shadows of the rings 1889 November 1.

Yet conflicting reports of the division's existence persisted into the twentieth century. Based on Pioneer 11's observation of the unilluminated side of Saturn's rings, Gehrels et al. (1980) continued to identify and discuss such a division. As observed in forward scatter, the claimed location, between 1.50 to 1.52 planetary radii, was second in brightness only to the dusty Cassini division. After the Voyagers, Esposito (1984: 470) described this as "… a region of increased transparency containing a number of opaque ringlets …" that was unlike other divisions. Based on Cassini observations, Joshua Colwell (pers. comm., 2005) commented that

> … the transition to the B ring inner edge is morphologically very similar to that at the inner edge of the A ring, and the outer C ring does look very much like the Cassini Division interior to the A ring.

He concluded, as did Barnard, that no division exists between the B and C rings.

Figure 9 compares Barnard's results to normal optical depths from Voyager 2 and Pioneer 11, as presented by Bill R. Sandel et al. (1982). In this figure no modern transmission curve is shown inside the C-D ring boundary because Pioneer 11 did not observe the D ring and because the D ring's intensity, according to the Voyagers, was very much weaker than the C ring.

Consequently, there is nothing to compare to Barnard within this boundary. The C ring is about 17,500 km wide. Barnard agrees with Voyager 2 and Pioneer 11 over the first 9,000 km, from 1.235 to about 1.384 planetary radii. Agreement means only that he anticipated the general trend of normal optical depth as measured by the spacecrafts. However, elsewhere there is disagreement. From 1.074 to 1.235 planetary radii his optical depths are greater than can be explained by the modern D ring. That he was accurate at this point must be inferred from his corroborated results in the nearby C ring where, from 1.235 to about 1.28 planetary radii, he obtained similar intensities. Another disagreement occurs from about 1.384 planetary radii to the B-C ring boundary where Barnard's values dramatically diverge into greater densities. He did not recognize this because he could not distinguish normal from abnormal densities in the C ring. His last nine positive magnitude estimates were made in the range 1.485 to 1.517 planetary radii when Iapetus approached and then entered the B-C ring boundary. These observations are significant because he saw Iapetus become fainter than Enceladus. That should not have happened as early as he saw it.

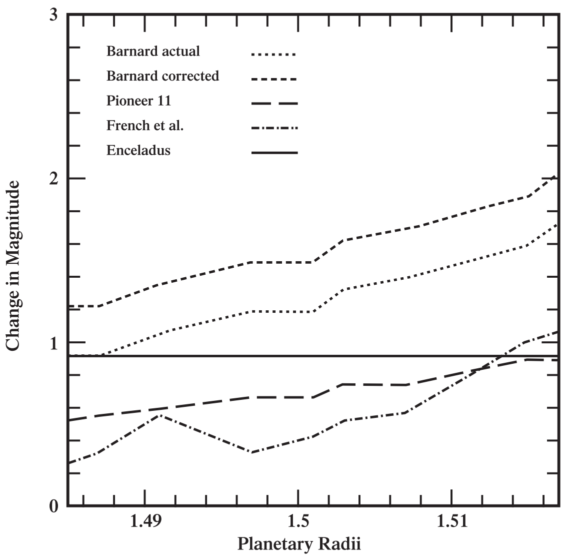

Figure 10: The plot compares Barnard's last nine differential magnitudes for Iapetus in eclipse to predicted differential magnitudes for the satellite based on modern optical depths for the C ring from 1.485 to 1.517 planetary radii. The unchanging magnitude of Enceladus (V = 11.8) is indicated for further comparison. Zero on the differential magnitude axis corresponds to Iapetus' magnitude outside eclipse (V = 10.9). Barnard saw Iapetus equal Enceladus at 1.485 and 1.487 planetary radii. Thereafter, Iapetus became fainter than Enceladus until he saw it disappear into the B ring's shadow. If the C ring's transmission characteristics in 1889 were as they are today, Iapetus should have equalled Enceladus' magnitude only near Barnard's last two observations at 1.515 and 1.517 planetary radii. As a complication, his magnitude estimates of Iapetus appear to be systematically too bright by about 0.3 magnitude due to position angle error, a fault peculiar to visual magnitude estimates in specific circumstances. Even with an apparent tendency to over-estimate its brightness, Barnard saw Iapetus become fainter than Enceladus too early. The C ring in 1889 might have been visually different than it is today, but another possibility is that spokes were present in the C ring at the time of the eclipse. At the B-C ring boundary the difference between Barnard's results and modern normal optical depths is about 0.1 which is similar to the observed density of spokes.

Figure 10 presents his last nine positive estimates of Iapetus as differences in magnitude. It relates Iapetus' observed magnitude during eclipse to its magnitude outside of eclipse and to predicted magnitudes based on modern optical depths for the C ring from 1.485 to 1.517 planetary radii. It also compares changing Iapetus to unchanging Enceladus. At 1.485 planetary radii Barnard estimated that Iapetus and Enceladus were equally bright. That is relevant for two reasons: the effect of position angle error on his estimates, and, most importantly, the implication of modern optical depths. Barnard identified Iapetus' peak visual magnitude at about 10.6. I correct that to V = 10.9 and apply the difference of 0.3 magnitude to his other estimates as a uniform correction for likely position angle error. Iapetus at V = 10.9 was about 0.9 magnitude brighter than Enceladus at V = 11.8. For the range 1.485 to 1.517 planetary radii, based on Pioneer 11 in Figure 6, the general trend of normal optical depth increased from about 0.07 to 0.12. Alternatively, Figure 5 shows approximately 0.04 to 0.14. Assuming that modern optical depths are relevant to the C ring in 1889, at 1.485 planetary radii, Barnard should not have seen equality. Iapetus was probably already fainter than Enceladus, with an approximate visual magnitude of 12.1. Only position angle error made it seem as bright as Enceladus. According to modern optical depths and without the effect of position angle error, he should have seen Iapetus to be brighter than Enceladus by 0.4 to 0.7 magnitude. The only moments during the C ring eclipse at which the two satellites should have been nearly equal were his last two observations at 1.515 and 1.517 planetary radii, very near the B-C ring boundary. However, by 1.517 planetary radii, despite his apparent over-estimates of its brightness, he still recorded Iapetus as about 0.8 magnitude fainter than Enceladus. At an opening angle of -8.49°, an increase in normal optical depth of about 0.11 could have affected Iapetus in this way. Modern optical depths imply that Barnard observed the C ring to be unusually dense over a large radial distance. If the ring has not significantly changed since 1889, another possibility is that something transitory affected it simultaneously with the eclipse.

Showalter (1998) observed transient clumps in Saturn's F ring. These appeared unexpectedly and faded in brightness over about two weeks. He interpreted them to be "… burst events …" and suggested that they are caused by high-speed impacts of approximately 10 cm-diameter meteoroids on ring bodies. Alternatively, burst events may be produced by relatively slow collisions among rubble pile moons (Barbara and Esposito, 2002).

With the equation

$$A' / A = (\pi r^2 N^{1/3}) / \pi R^2, \quad (5)$$

it can be shown that a cloud of particles from the destruction of a small moon could produce a shadow that would reduce Iapetus' magnitude by 14% as Barnard observed just before the satellite entered the shadow of the C ring. Where A'/A is the ratio of the area obscured by the particle cloud to the area of Iapetus, r is the radius of the disrupted moon, R is the radius of Iapetus, and N is the number of particles created in the burst event, the equation shows that for moons with radii of 5 and 10 km, 2.4×10^{10} and 3.8×10^8 particles, respectively, spread across the area of Iapetus (1.6×10^6 km^2) would cause 14% obscuration.

However, even if objects with radii of 5 to 10 km exist in the outer D ring, this scenario does not explain Barnard's situation. What he observed involved a very much larger area. Ring spokes can cover large areas.

8 RING SPOKES

Spokes are tenuous, dark, ephemeral objects that appear to be "… confined to the central B ring with an inner boundary at 1.72 ± 0.01 … [planetary radii] and an outer boundary at approximately the outer edge of the B ring." (Smith et al., 1982: 535). Maximum radial and azimuthal dimensions of 8,000 and 20,000 km, respectively, have been observed, but narrow and filamentary shapes also occur (Grün et al., 1983). They are dark in back-scattered light and bright in forward scatter which indicates that they consist of fine dust. Spokes appear at any azimuth on the rings but most often at the eastern or morning ansa. They last for about one-fourth to one-third of the orbital period of the magnetic field (de Pater and Lissauer, 2001), 10 hours 39.4 minutes. Their typical normal optical depth is about 0.1 (Grün et al., 1983).

There is no consensus for the cause of spokes (de Pater and Lissauer, 2001), however, they are thought to be charged dust particles with a size of a micrometer or less that are levitated over the rings through electrostatic repulsion. Their radial orientation seems to last as long as dust is being added, but they spread and become patchy through loss of dust and Keplerian motion. Spokes are active at and near the corotation distance, 1.86 planetary radii, where Keplerian circular velocity equals the planet's angular velocity as defined by the rotational period of the planet's magnetic field. Carolyn Porco and Edward Danielson (1982) and Porco (1988) found that changes in the appearance of spokes are correlated with the orbital periods of the magnetic field and of broadband radio emissions called Saturn Electrostatic Discharges. Even so, Christoph Goertz and Gregor Morfill (1983) urged that gravity, not electromagnetic force, dominates the motion of ring dust particles. They proposed that dense plasma columns are created as meteoroids impact ring bodies and that these columns eventually corotate with the planet's magnetic field. Charged dust particles in the plasma cloud are electrostatically expelled from their resting places in the ring when the electric force becomes stronger than gravity. Colleen McGhee et al. (2005: 517, 508) examined the photometric properties of spokes as recorded in Hubble Space Telescope (HST) images from 1994 to 2004. Spokes were visible on either side of ring plane crossing but became fewer and fainter until no spokes were observed beyond an opening angle of -15.43º. After modeling alternative arrangements of dust relative to the rings, they concluded that "… the strong tilt effect on spoke contrast can be accounted for as a result of varying viewing and illumination geometry of an extended layer of dust that lies above the ring itself." Although they predicted that "… spokes should be easily detectable during the Cassini mission when the rings are viewed at relatively small ($|B| \leq 10°$) ring opening angles …" it took from July 2004, when Cassini achieved orbit, until September 2005 before the spacecraft observed spokes. These appeared on the dark side of the rings when the angle to the spacecraft was 13.5° (Mitchell et al., 2006: 1587). Colin Mitchell and Mihaly Horányi (2005: 1) proposed

> … that the absence of spokes [earlier in the mission] is due to a seasonal modulation of the plasma environment in the rings. The photoelectron density above the rings is determined by solar irradiance, hence the elevation angle of the Sun.

Porco et al. (2005: 1229) further described the plasma environment.

> High Sun creates a layer of photoelectrons above the rings that can negatively charge small dust particles above the rings, pulling them back to the (positively) charged rings. A low … [Sun] angle reduces the … photoelectron layer, causing dust particles to have a net zero (or slightly positive) charge and therefore to be repelled by the … ring. The relatively high Sun elevation at present may create an environment hostile to the appearance of spokes.

Mitchell et al. (2006: 1589) anticipated that spokes will be seen in mid to late-2006 "… if the plasma conditions are favorable for their formation and either the observer or the Sun is near the ring plane."

Barnard's observation is consistent with three properties of spokes. First, spokes are best seen at low opening or solar illumination angles. McGhee et al. (2005: 517) found that "… a relatively low optical depth … is sufficient to produce the observed contrast [between spokes and their surroundings] …" when viewing or solar illumination angles are small. For Barnard, a relatively low angle deepened ring shadows on Iapetus presumably making it easier for him to see changes in illumination. Secondly, spokes can occupy long radial distances and broad areas. His transmission curve identifies what could be interpreted as two radially extended features that were superimposed upon the B, C, and D rings. The D ring feature had a radial extent of about 9,000 km. The orbital period is about 5.3 hours in the middle D ring. Since Iapetus took about 35 minutes to transit the feature, spokes would have had to extend about 40° or 49,000 km along the arc of the ring. The C ring feature covered at least 7,500 km and continued into the B ring. At a radius of 90,000 km the orbital period is about 7.7 hours. Iapetus took about 40 minutes to transit the feature. Spokes would have had to extend about 30° or 47,000 km along the arc of the C ring. Thirdly, spokes have normal optical depths of about 0.1. What Barnard saw had a normal optical depth of about 0.1 at its densest point on the B-C ring boundary. Nevertheless, to explain his observation with spokes is unconventional. Planetary scientists believe that they are limited to the central B ring.

Evidence for spokes in the B ring and for spoke-like features in the A and C rings has been collected by visual observers for a long time. Stephen J. O'Meara is the most successful visual observer of spokes. Beginning in 1976 he used 9 and 7.25-inch refractors to visually estimate 0.1 magnitude azimuthal variations in the brightness of the A ring. Observing in twilight to diminish the apparent brightness of the A ring, he unexpectedly found dark radial features in the B ring. These had the rotational period of the planet and did not exhibit Keplerian motion. They tended to prefer the morning ansa and their visibility was related to ring opening angle. His reports were disbelieved, and his attempts to publish were refused. After the Saturn Conference in Tucson, Arizona in May 1982 O'Meara was recognized for his results, but these made no lasting impression outside amateur astronomy even when events were fresh:

> Visual observers have also occasionally claimed to see transient, dark radial features and bright spots in the rings (Alexander 1962). These reports are especially intriguing in the light of Voyager discovery of spokes … however like many other visual reports, they are difficult to assess objectively. (Cuzzi et al., 1984: 75).

What O'Meara did entitled him to discovery credit, but historically others came close to that distinction.

9 HISTORICAL OBSERVERS AND O'MEARA

Barnard did not believe that dark features on Saturn's rings were real. Even so, his result for the eclipse of Iapetus appears to be consistent with claimed activity in the C ring in the years around 1889. It was a routine matter for nineteenth-century observers to describe apparent changes in Saturn's rings. By the middle-twentieth century, however, Alexander's (1962) comprehensive analysis of the historical record explained many unusual claims as unreal effects created by illusion and error. While Alexander made valid points, he did not have the advantage of knowing that spokes in the B ring are real. Further, the Cassini-Huygens mission makes clear that spokes are difficult to explain. Interesting and perhaps significant historical examples of reported change in the rings include the following episodes.

Trouvelot (1877: 191) identified spoke-like features in what he called the B ring but that is now known as the A ring:

> … the inner margin of the [A] ring … limiting the outer border of the principal [Cassini] division, has shown on the ansae some singular dark angular forms … the surface of the [A and outer B] rings … has shown a mottled or cloudy appearance on the ansae during the last four years …

François J.C. Terby (1887: 163) announced the presence of "… masses sombres dans l'anneau obscur …" (big dark blotches in the dusky ring). Not everyone was convinced, but Thomas G.E. Elger (1887: 512) was emphatic about their reality:

> 26th February [1887] … the p[receding] ansa [of the C ring] exhibits on its inner border three or four large re-entering angles like the teeth of a saw, the intervening spaces being apparently as dark as that between the ball and the ring, and extending nearly to the outer edge of the ring. 12th March [1887] … p ansa is very evidently broken up into several areas of different degrees of darkness, so that, except a short section of it, np, it is impossible to recognise it as a ring surrounding the planet. The f[ollowing] ansa … is easily visible.

In April 1890, about six months after the eclipse of Iapetus when the rings were slightly more open, Paul Stroobant (1890) observed dark notches with puzzling shapes on the inner edge of the evening ansa of the C ring. In April 1896 Eugène M. Antoniadi (1896: 339), reported, "… instead of the Encke division, ring A shows (just now) some enormous white spots separated by dusky intervals. This ring appears broken (as it were) into fragments." In June he added that the "… [A] ring showed itself lately composed of successive groups of white spots, separated by dusky intervals, which seemed to shoot forth in the direction of radii emanating from Saturn's centre." (Green, 1897: 240). Others saw similar effects. Charles Roberts (Green, 1897: 244) reported that

> … the serrated appearance of this [A] ring where it borders Cassini's division was seen with great certainty on several nights … [On] June 28, the inner edge of ring A looked … sharp. On July 3 some very conspicuous serrations were seen on the f. ansa … On May 8 the inner edge of the p. ansa [of ring C] appeared serrated somewhat like that of ring A …

Rev. T. H. Foulkes (Green, 1897: 237) left this record:

> Noticed a remarkable appearance of the [C] ring where it crossed the ball, it did not possess its usual uniform appearance, but was decidedly 'lumpy.' I counted six or seven of these darker shadings, which seemed to have a tendency to circular formation … Though … [I have observed Saturn] for the last 25 years, I have never before seen this curious formation.

However, Foulkes' observation may be unrelated to the C ring. In 1993 Richard McKim (pers. comm., 2005) and others saw similar clumping in the C ring. They did not suspect changes in the ring. Instead, they preferred the possibility that dark spots in the North Equatorial Belt, which lay beneath the ring, were visible through it. An observation by the Cassini spacecraft on 28 April 2006 appears to justify that interpretation. Bright clouds in the planet's atmosphere were only partially obscured by the shadow of the C ring (NASA/JPL/SSI, 2006).

Barnard (1895: 369-371), who saw none of this, was not persuaded. He treated the matter with sarcasm:

> The Crape ring has appeared uniformly even in shade at the two ansae. It was of a steelly blue colour, and was not strongly contrasted with the sky. No markings whatever were seen upon it. The inner edge was a uniform curve; the serrated or saw-toothed appearance of its inner edge, which had previously been seen with some small telescopes, was … beyond the reach of the 36-inch.

Considering the vivid drawings of Saturn that others produced, Barnard was unapologetic for his own art that "… appears abnormally devoid of details … I am satisfied, however, to let it remain so." His assessment of results by George Davidson, a San Francisco amateur astronomer, could have applied to his own: "One great thing must commend itself to every observer familiar with Saturn in a telescope is that he has not shown a single abnormal feature." Although he apparently did not know it, his situation was not so simple.

On 7 January 1888, the night of the first successful test of the 36-inch refractor, James E. Keeler drew an image of Saturn that became known as "… the best existing picture of the planet for many years, and [that] was widely admired by professional astronomers of the time …" (Osterbrock and Cruikshank, 1983: 168). As Keeler drew it, the B ring had three faint, dark, diffuse, radial shapes upon it that suggest spokes. The shapes are not obvious and are only noticeable as departures from circularity within the ring. It was Barnard's opinion that Keeler had artistic ability that few other observers possessed (Sheehan, 1995: 149). There is every reason to suppose that he drew the B ring just as he saw it, including the likeness to faint spokes. Sheehan (1988: 133) also thought that his drawing "… gives hints of the 'spokes' on the surface of Ring B …" Keeler eventually presented a copy of his famous drawing to Barnard as a gift (Osterbrock and Cruikshank, 1983). In receiving it, Barnard had evidence that odd features on Saturn's rings were well within reach of the 36-inch refractor. Surviving letters written by Keeler to Barnard, now collected at Vanderbilt University, do not discuss the Saturn drawing. Since Keeler's observing record for January 1888 is lost, it is not possible to know what he thought about the appearance of the B ring.

Historical observers tend to differ with O'Meara over the intensity of transitory dark ring features. Elger is a good example. He insisted upon the obviousness of these objects and drew them vividly (Figure 11). O'Meara (pers. comm., 2005) emphasized their subtle appearance, but drew them just as vividly (Figure 12):

> I've never seen black markings or gauges. And I'm certain no one in history has (not even Elger). You have to consider the artist's style when he or she is trying to portray a dim feature. For instance, even in my drawings, the spokes look very intense, but they are not. They are definite but delicate to the eye, very hard to render in a way that will reproduce, unless you intensify them.

Elger was an experienced lunar and planetary observer, and it is certainly possible that he meant exactly what he wrote. The degree to which something is obvious depends, after all, on the observer. However, Elger had critics who saw no dark features. They suggested that either his equipment or his eyesight was faulty. Elger (1888) replied that only dabblers in Saturn could fail to see what he reported. Disagreement that declined into personal jabs makes it possible, even likely, that some of his emphasis was intended to defeat critics. Then differences over intensity may be an effect of non-observational influences such as the need to create a reproducible illustration or the desire to make a point. Not all the historical cases are so. Although Keeler apparently made no claim for dark features, his drawing is consistent with tenuous spokes in the B ring as O'Meara described. However, visual observations, both historical and modern, disagree with two presently-accepted conditions for spokes—that they occur only in the B ring, and that their visibility is limited to small ring opening or solar illumination angles.

10 A DIFFERENT PERSPECTIVE

Are spokes confined to the central B ring? O'Meara (pers. comm., 2005) described the A ring as being prone to ephemeral shaded patches. He has seen "… Ring C appear patchy at times in larger scopes." At Pic du Midi on 1-2 August 1992, he saw "… two dark radial features on the southeast quadrant of Ring C—not at the ansa … The preceding [evening] ansa looked uniform." These features were azimuthally associated with but were not connected to five B ring spokes that had a saw-toothed and curved appearance:

> They were radial but certainly different than those in Ring B … [being] broader and more linear … I … [recall] their dimness. The spokes in Ring B were much more obvious … because … I was looking at a 'dark' shading against a bright ring … in Ring C, I was observing 'slightly darker' features against a relatively dark ring, which is much harder to do … I had to use averted vision to see them … I believe this might be why Bill [Sheehan, who saw the five B ring spokes] did not see the features in Ring C.

Sheehan (pers. comm., 2005) did not look for spokes in the C ring.

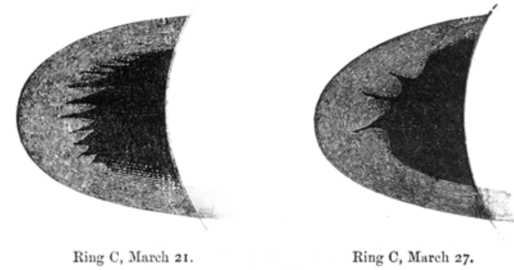

Figure 11: Engraved drawings of the C ring from March 1888. In 1887 and 1888 Thomas Elger was one of several observers who reported unusual dark markings on the C ring. Their existence was controversial. Elger (1888) described what he saw as follows: "March 21 … Inner edge ragged and clearly indented on p. side, but indentations not very deep … March 27 … Inner edge on p. ansa scalloped, exhibiting three or four convex projections, and dark patches visible on its surface." South is up in these images. If the engravings are faithful to Elger's original drawings, the dark features had an angular extent along the ring that approached 45°. Taking into account rotation rates in the C and D rings, what Barnard observed 19 months later during the eclipse of Iapetus must have had a similar extent to have affected his observation as it did. (Reprinted from "Physical observations of Saturn in 1888" by T.G. Elger, *MNRAS*, 48, 362-370, 1888, figure entitled "Ring C, March 21 [and] Ring C, March 27" with permission from Blackwell Publishing.)

Is the visibility of spokes limited to small ring opening angles? McGhee et al. (2005) detected no spokes beyond an opening angle of -15.43°. In August 1988, when the angle was about 26°, O'Meara (pers. comm., 2005) observed spokes with the Mount Wilson 1.5-m telescope. He described their color as ice blue. In August 1992 he used the 1-m telescope at Pic du Midi. On that occasion, when the angle was about 16°, he described spokes as gray in color and stronger in appearance than they had been in the 1.5-m. Presumably, changed opening angle affected his sense of the color and contrast of spokes. In both cases opening angles were in excess of 15°. One of his earliest observations of spokes was made at an opening angle of about 18° (Robinson, 1980). As to smaller angles, he saw spokes in greatest numbers from October 1976 to March 1978 when the angle closed from about -17° to -12°. He saw far fewer spokes from November 1978 to January 1979 as the angle changed from about -5° to -4°. His count increased again from February to June 1979 when the angle opened from about -5° to -7°. Unlike McGhee et al. (2005), who continued to detect spokes between angles of +4° and +5°, very narrow viewing geometry was a disadvantage for O'Meara.

Why were O'Meara's results different? While the spoke process apparently has a time-scale of years that is related to solar illumination of the rings, individual spokes clearly exist and change on a time-scale of minutes and hours. To observe spoke dynamical changes with HST, Bradford Smith (1984: 709-710) anticipated that orbital limitations would impose non-continuous data sets so that

> … we cannot escape … the same problems encountered with the Voyager images. Statistically, one can partially overcome the problems of a 0.4 observing duty cycle by extending the total observing time. Typical spoke lifetimes are ~5 hr … and thus the accumulation of several tens of hours of observing time by recording the rings for 30-45 minutes per orbit would likely yield many … [spoke events] … the Voyager data have

taught us that sporadic observations are of relatively little value for dynamical studies.

McGhee et al. (2005: 508) observed the planet with several hundred high resolution images obtained on 34 dates from 1994 to 2004. They identified "… 36 spokes or spoke complexes, predominantly on the morning (east) ansa." From 1976 to 1983 O'Meara observed several times each week during apparitions of the planet. Representative of his pace, O'Meara (pers. comm., 2005) observed 29 spokes in a period of 43 days from 24 January to 8 March 1977. If gaps in coverage on a time-scale of hours prevent correct understanding of spoke dynamics, gaps that range to months must interfere with understanding other properties. That O'Meara reported spokes outside the B ring and at large ring opening angles while planetary scientists through January 2004 observed neither does not necessarily mean that he was wrong. It may be that his rate of observation made a meaningful difference.

Figure 12: Saturn as drawn by Stephen J. O'Meara on 1-2 August 1992 at the 1-m telescope of Pic du Midi Observatory. O'Meara saw spokes in the B ring. He also saw even fainter spoke-like features in the C ring, but in this image he exaggerated their density for clarity. O'Meara is not first to record such activity in the C ring. In the 1880s and 1890s astronomers argued the reality of claimed transitory dark features in that ring. Illustrative of the challenge that spokes present to visual observers, O'Meara put the planetside edge of B ring spokes in contact with the B-C ring boundary. Other observers have done the same. However, spacecrafts show spokes in the central B ring that are not in contact with the B-C ring boundary. Visual observers may not be able to distinguish the darkness of spokes from the darkness of the inner B ring leading to a perception that spokes reach the B-C ring boundary. As shown here, north is up (courtesy: Stephen J. O'Meara).

11 WHY NOT BARNARD?

The ring system appears to have been visibly active in years before and after the eclipse of Iapetus. If that is true, did Barnard see anything unusual on the rings during the eclipse? He described what he saw:

> The superb definition of the planet in the last part of the observations showed no abnormal appearance of the rings where the shadow of the ball crosses them, nor have I at any time seen a white spot on the rings at this or any other point. (Barnard, 1890).

The white spot Barnard referred to was a contrast effect seen seven months earlier by Terby. He said nothing about dark features on the rings. If spokes were there, why did he not see them?

Barnard left no indication that he anticipated anything other than an exhibition of the C ring's normal transmission characteristics, but it would not have been excessive for him to have wondered about possibilities. The advantage of being first to observe the inner ring system in transmission was more than enough reason to anticipate something new. Yet his first report to the Astronomical Society of the Pacific was so narrowly directed to Marth's question about the C ring as to imply that he had only one purpose on his mind, so much so that he may have overlooked subtle spokes. How likely is that? Using a telescope of comparable size, O'Meara (pers. comm., 2005) found that when his attention was directed to ring divisions, he could not see spokes that were present on the rings. The converse was also true.

Barnard observed with a magnification of 150×. O'Meara (pers. comm., 2005) believes that this is too low a power to distinguish spokes on the bright B ring, especially at night as opposed to during twilight. In O'Meara's case, 250× was probably the minimum useful magnification with 275× to 350× being better. Because spokes are delicate and their surroundings are bright, he often "… would observe only one side of the rings … at a time …" by using the edge of the field as an occulting bar. Historically, Elger (1887) worked in the range 284× to 420×, Antoniadi used 220× to 600× with a preference for 300× (Green, 1897), and Stroobant (1890) used 360×.

Another factor concerns what Barnard could see on planets. People respected and were sometimes amazed by his visual observations, but they were also vexed by what they thought he could not see. Barnard's successses and access to the world's largest telescopes encouraged him to assume superior authority in answering observational questions. He was not reluctant to disappoint others over their claimed discoveries. Because those whom he contradicted included experienced planetary observers, there was an inevitable consequence. According to Antoniadi (1909a), "… Barnard n'est pas un observateur de détails planétaires délicats …" [Barnard is not an observer of delicate planetary details]. Others agreed. Given his record, did he really not see what others saw?

Antoniadi criticized on the occasion of Barnard's inability to see a fourth ring reported by Georges Fournier to be just outside Saturn's A ring. Antoniadi (1909a: 450) sardonically observed that since the new ring

> … a été absolument invisible à l'illustre découvreur … on conviendra qu'il ne saurait plus être question de

> l'existence d'un anneau extérieur crépusculaire de Saturne. [… is absolutely invisible to the great discoverer … we will agree there can be no question of whether or not Saturn's exterior crepe ring exists].

With similar bite, he alluded to another disagreement in the 1890s when Barnard could not see spots in Saturn's atmosphere that were reported by Arthur Stanley Williams, "… one of the most outstanding non-professional astronomers of modern times …" (Obituary, 1939: 313-314). That disagreement was as much sociological as it was observational. Professionals were replacing amateurs as leaders in astronomy. Barnard, who used a great telescope, and Stanley Williams, who used a small one, produced "… scientific knowledge … [that] rested on strikingly different perceptions of the natural world." (Lankford, 1981: 27). A conclusion for the reality or unreality of the spots depends on which facts are emphasized. However, one result was certain. Some European astronomers were sure that they had found the limit of Barnard's ability.

Barnard did not see obvious geometrical patterns of canals on Mars as did Percival Lowell, but he was not alone. In contradiction of the consensus that there are no Martian canals, Dobbins and Sheehan (2004: 117) found that

> … many of the canals appear to be artifacts of edge enhancement of the boundaries of adjoining regions of different albedo that correspond physically to adjoining surfaces strewn with bright or dusky surface materials.

That canals exist as indistinct features is an old idea. Giovanni V. Schiaparelli depicted them with sharp lines, but Nathaniel Green (1880: 332), observed them to be "… boundaries of faint tones of shade, so delicate that they escape the notice of any but a well-trained eye …" Green (1890) complained that those who drew canals as distinct lines did not represent them as they actually saw them. The canal debate was in full swing in 1909 when Antoniadi mocked Barnard over a fourth Saturnian ring. Similar to Green and Dobbins and Sheehan, Antoniadi (1909b) saw canals as "… the optical products of very complex and irregular natural duskiness sporadically scattered all over the Martian surface." He opposed Lowell's unnatural geometrical canal network. Now Antoniadi (1909b) wrote to Barnard, "… with the highest admiration for your genius …" that he was honored "… to find that we are in perfect agreement regarding the appearance of the so-called 'canals' of Mars." Further, "… you called my attention to the fact that the streaks of Mars appeared to you larger in great telescopes than they were drawn with small instruments." (Antoniadi, 1910). As for Lowell, who rebutted all who did not see canals as he saw them, Barnard's observational talent was better suited to faint stars and star-like objects than it was to planetary surface markings (Sheehan, 1988). It seems clear that others' opinions of Barnard's visual skill at the telescope were influenced as much by self-interest as by what there was to see.

Assuming that spokes were there to be seen during the eclipse of Iapetus, insufficient magnification and Saturn's brightness are likely reasons why Barnard did not see them. He may also have been too preoccupied to notice them. It is true that he never saw transient dark markings on Saturn's rings. However, rather than conclude that these were beyond him, it seems more likely that he suffered from bad timing with ephemeral objects. While it would be helpful or even final if Barnard had seen wispy, dark features on the morning side of Saturn's rings during the eclipse, that he saw none is unrelated to his ability to estimate Iapetus' magnitude in eclipse. His record demonstrates that faint stars and star-like objects were less of a problem for him than they were for others (Burnham, 1889; Sheehan, 1988).

12 EVALUATION AND CONCLUSION

I have relied on visual observations to speculate on the meaning of Barnard's observation of the eclipse of Iapetus, but visual observations are problematic evidence. They are subjective. Without independent confirmation, their scientific significance is arguable. Most importantly, the visual method has lost credibility among professional astronomers so that it is difficult to make any point that is visually supported:

> Although groundbased observers had reported seeing streaks in the A ring as early as 1873 (Alexander, 1962) and had even computed a rotational period for features seen in the B ring in the 1970s (Robinson, 1980), the B ring's vast panorama of spokes seen in the Voyager images was unexpected. (McGhee et al., 2005: 509).

It was unexpected because historical and modern visual observations, that constitute knowledge of spokes prior to Voyager 1, were too different from the experience of planetary scientists to be taken seriously.

I have considered the possibility that Barnard saw ring shadows mixed with spoke shadows on Iapetus because he observed at a time when the C ring was apparently affected by spoke-like activity. Observers have seen transient objects in Saturn's rings for 133 years. Nevertheless, planetary scientists largely ignore the visual record. Historically, when scientists could not collect information for themselves, they were obliged to receive it from other people and to evaluate its credibility. If the visual history of spokes recalls the old problem of knowing what to do with observational evidence contributed by others, perhaps an old answer still applies. Steven Shapin (1994: 212) identified criteria that were once used to test the credibility of contributed information. The criteria are common sense that remains familiar. A contribution may be credible if it:

1. Is plausible.
2. Comes from multiple sources.
3. Is without internal or external contradiction.
4. Is first-hand to the contributor.
5. Comes from knowledgeable, skilled, disinterested, and honest persons.

Consider O'Meara's situation before Voyager 1. A young person with an old telescope saw in the A and B rings transitory, faint, diffuse, dark, radially-oriented objects with non-Keplerian orbital motion. These had a period similar to the planet's rotation rate. The objects preferred the morning ansa of the rings, but also appeared on the evening ansa. He saw them in greatest numbers at intermediate and small ring opening angles and watched their numbers apparently decline as the angle became very small. Although his result was firsthand, it was not plausible, came from him alone, and contradicted fundamental knowledge of the ring system. Further, astronomers whom O'Meara consulted either did not know him or did not fully trust him. Although it was substantially correct, his result was too strange and too unsatisfactory to be believed before Voyager 1. That outcome was either an understandable mistake or appropriate conservatism. Either way, a fundamentally correct description of a previously-unknown phenomenon of the ring system was disbelieved.

The prospects for Barnard after the eclipse of Iapetus were entirely different. Unlike O'Meara, he was well known as a planetary scientist. In 1889 his form of photometry was generally accepted, his instrumentation was suitable, and his application was novel. Nobody published doubt over the correctness of his result and conclusion even though he alone saw the eclipse. Barnard's three published accounts show that he was in a dilemma over interpretation of what he saw. Either the anomalous decline in Iapetus' magnitude before the C ring eclipse was real or it was not. If he called it real, what explained it?

An interpretation that remained attractive until Pioneer 11 visited Saturn in 1979 was that he had observed the shadow of an unseen ring interior to the C ring. If he had made that claim, it would have been plausible because the relatively recent discovery of the C ring made the existence of another tenuous interior ring believable. It would have contradicted no established fact about the ring system. His evidence was first-hand. He had a first-rate international reputation as a skillful and conservative observer and discoverer. The only obvious fault was lack of independent confirmation. Presumably, with four out of five favorable indications, a majority of his colleagues would have been justified to believe him. However, Barnard, who preferred to avoid critics, offered no opportunity for others to evaluate what he had seen. He never suggested the existence of an unseen ring. He certainly did not associate his observation with controversial dark spots on the C ring for he publicly rejected their reality. He refused to believe that the first 30 of his 75 magnitude estimates of Iapetus revealed anything unknown about the ring system. Did he sacrifice a meaningful observation because it was unexpected, extraordinary, and not confirmable? Common sense and his own considerable experience must have guided his decision, but as was true at other times, his fear of ridicule may also have been at work. The conservative answer was safe, but did it downplay a real phenomenon as happened in O'Meara's case.

The conjecture that Barnard saw spoke shadows on Iapetus contradicts modern scientific understanding of where spokes occur. It is otherwise consistent with the normal optical depth of spokes, their increased contrast at small ring opening angles, and their ability to cover long radial distances and broad areas. It appears to be consistent with observations of transitory dark markings on the C ring in the late 1880s as well as with a similar case in 1992. See Figure 13 for an observation made by Stroobant a few months after the eclipse of Iapetus. However, even if this interpretation is wrong, I urge that two aspects of Barnard's observation are significant. He saw Iapetus begin to fade before it reached the C-D ring boundary. He also saw Iapetus become fainter than Enceladus too soon. Apparently, a condition existed in the inner ring system on 1-2 November 1889 that does not, for whatever reason, exist now.

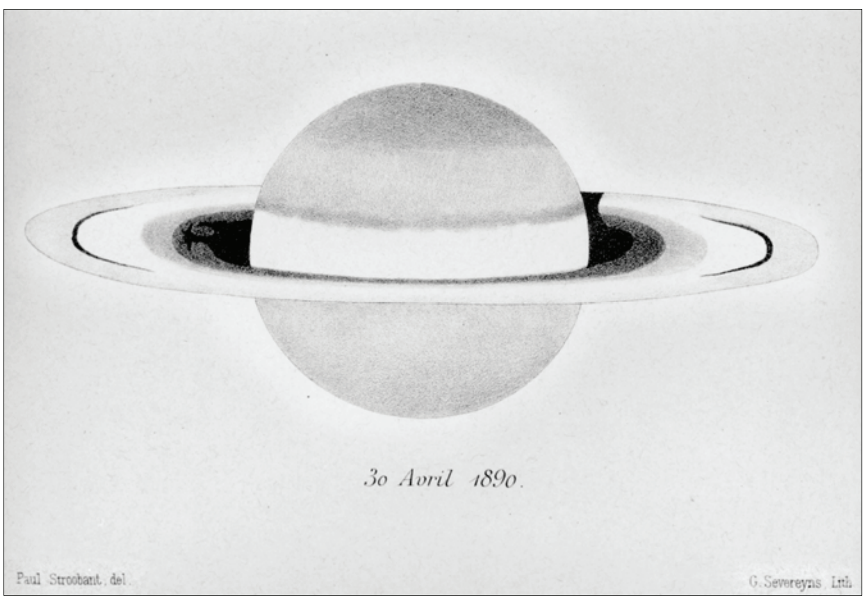

Figure 13: On 30 April 1890 Paul H. Stroobant (1890) drew Saturn and its ring system. The opening angle on the rings was about -11°, only slightly more open than what Barnard saw about six months earlier. Stroobant described the western ansa of the C ring as displaying two dark notches. The notch at the middle of the ansa had " … une forme dont il était difficile de saisir les contours exacts" [… a shape that made it difficult to grasp the exact contours]. What is the significance of dark markings in the C ring that were seen by Terby, Elger, Stroobant and others? If they were real, were they spokes? If spokes were present in the inner ring system during the eclipse of Iapetus in 1889, would they have affected Iapetus' brightness in eclipse as Barnard recorded it in his light curve? The irregular shape that Stroobant drew for the planet's shadow on the rings is incidentally relevant. The shadow is naturally curved, but observers sometimes report non-curved shapes. In the nineteenth century some thought these anom-alous shapes were produced by topography on the rings, but for most of the twentieth century non-curvature was dismissed as an illusion. Modern critics have suggested that awareness of non-curvature may indicate an observer's susceptibility to illusion. However, Mark Bailey, David Stewart and Mark Stronge (2005) now explain non-curvature of Saturn's shadow as an optical phenomenon like the black drop in transits of Venus (after Stroobant, 1890: insert between Pp. 774 and 775, figure entitled "30 Avril 1890" with permission from the Council of l'Academie Royale des Sciences, Lettres et Beaux-Arts de Belgique).

13 ACKNOWLEDGEMENTS

I thank the following people for their help. Stephen O'Meara described in detail his visual observations of spokes. Amanda Bosh, Joshua Colwell, Jeffrey Cuzzi, Richard French, Mihaly Horanyi, Mark Showalter, Laurence Trafton and Anne Verbiscer answered scientific questions. John Isles advised on visual estimation of stellar magnitudes. William Gray computed various circumstances for the eclipse of Iapetus. Francis Everitt answered questions about James Clerk Maxwell. For copies of documents and other information by and about Barnard, Clerk Maxwell, Keeler, Marth and Maunder, I thank Dorothy Schaumberg and Cheryl Dandridge at the Mary Lea Shane Archives for Lick Observatory; Teresa Gray at Special Collections and University Archives for Vanderbilt University; Peter Hingley and Mary Chibnall at the library of the Royal Astronomical Society; [Dr.] Stephen W. Taylor, B.A., Ph.D., a historical researcher and genealogist in the United Kingdom; Jane Wess at the National Museum of Science and Industry; and Joanna Ball at Trinity College Library. Richard Dreiser at Yerkes Observatory provided a copy of Keeler's January 1888 drawing of Saturn. Howard Adkins did artwork for the figures. Finally, I thank Harold Corwin, Jeffrey Cuzzi, Jay Holberg, Richard McKim, Stephen O'Meara, William Sheehan, Anne Verbiscer and Tom Williams for comments on a draft of this paper.

14 REFERENCES

Alexander, A.F.O'D., 1962. *The Planet Saturn: A History of Observation, Theory, and Discovery*. New York, Faber & Faber.

Antoniadi, E.M., 1896. Appearance of Saturn's rings. *Journal of the British Astronomical Association*, 6, 339.

Antoniadi, E.M., 1909a. Corpuscules en dehors du plan de l'anneau de Saturne. *Bulletin de la Société Astronomique de France*, 23, 448-450.

Antoniadi, E.M., 1909b. Letter to E.E. Barnard, dated 11 December. Vanderbilt University Special Collections, E.E. Barnard papers.

Antoniadi, E.M., 1910. Letter to E.E. Barnard dated 14 December. Vanderbilt University Special Collections, E.E. Barnard Papers.

Argelander, F., 1844. Aufforderung an Freunde der Astronomie. In Schumacher, H.C. (ed.). Jahrbuch für 1844. Stuttgart und Tübingen, J.G. Cotta'sche Buchhandlung. Pp. 183-254.

Bailey, M.E., Stewart, D., and Stronge, M., 2005. Extending the black drop to Saturn. *Astronomy & Geophysics*, 46, 1.7.

Barbara, J.M., and Esposito, L.W., 2002. Moonlet collisions and the effects of tidally modified accretion in Saturn's F ring. *Icarus*, 160, 161-171.

Barnard, E.E., 1889a. Logbook 24, Lick Observatory 12-inch equatorial, Oct. 2-Nov. 1, E.E.B. Observer. Lick Observatory, Mt. Hamilton.

Barnard, E.E., 1889b. Eclipse of Japetus, the VIII satellite of Saturn, on November 1, 1889. *Publications of the Astronomical Society of the Pacific*, 1, 126-127.

Barnard, E.E., 1890. Observations of the eclipse of Iapetus in the shadows of the globe, crape ring, and bright ring of Saturn, 1889 November 1. *Monthly Notices of the Royal Astronomical Society*, 50, 107-110.

Barnard, E.E., 1892. Transparency of the crape ring of Saturn, and other peculiarities as shown by the observations of the eclipse of Japetus on November 1st, 1889. *Astronomy and Astro-Physics*, 11, 119-123.

Barnard, E.E., 1895. Micrometrical measures of the ball and ring system of the planet Saturn, and measures of the diameter of his satellite Titan. Made with the 36-inch equatorial of the Lick Observatory. *Monthly Notices of the Royal Astronomical Society*, 55, 367-382.

Blair, G.N., and Owen, F.N., 1974. The UBV orbital phase curves of Rhea, Dione, and Tethys. *Icarus*, 22, 224-229.

Bosh, A.S., and Olkin, C.B., 1996. Low optical depth features in Saturn's rings: the occultation of GSC5249-01240 by Saturn and its rings. *Bulletin of the American Astronomical Society*, 28, 1124.

Brush, S.G., Everitt, C.W.F., and Garber, E., 1983. *Maxwell on Saturn's Rings*. Cambridge, MIT Press.

Burnham, S.W., 1889. The trapezium of Orion. *Monthly Notices of the Royal Astronomical Society*, 49, 352-358.

Chambers, G.F., 1889. *A Handbook of Descriptive and Practical Astronomy. Volume 1. Fourth Edition*. Oxford, Clarendon.

Chandler, S.C., Jr., 1885. The change in the great nebula in Andromeda. *Science*, 6, 247-248.

Clerk Maxwell, J., 1857. Letter to William Thomson, dated 1 August. Glasgow University Library, Kelvin Papers M7.

Cook, A.F. II, and Franklin, F.A., 1958. Optical properties of Saturn's rings: I. Transmission. *Smithsonian Contributions to Astrophysics*, 2, 377-383.

Cox, A.N. (ed.), 2000. *Allen's Astrophysical Quantities. Fourth Edition*. New York, Springer-Verlag.

Cuzzi, J.N. et al. 1984. Saturn's rings: properties and processes. In Greenberg, R., and Brahic, A. (eds.). *Planetary Rings*. Tucson, University of Arizona Press. Pp. 73-199.

de Pater, I., and Lissauer, J.J., 2001. *Planetary Sciences*. Cambridge, Cambridge University Press.

Dobbins, T.A., and Sheehan, W., 2004. The canals of Mars revisited. *Sky & Telescope*, 107, 3, 114-117.

Elger, T.G.E., 1887. Physical observations of Saturn in 1887. *Monthly Notices of the Royal Astronomical Society*, 47, 511-515.

Elger, T.G.E., 1888. Physical observations of Saturn in 1888. *Monthly Notices of the Royal Astronomical Society*, 48, 362-370.

Esposito, L.W., et al., 1984. Saturn's rings: structure, dynamics, and particle properties. In Gehrels, T., and Matthews, M.S. (eds.). *Saturn*. Tuscon, University of Arizona Press. Pp. 463-545.

Ferrín, I.R., 1974. Saturn's rings. I. Optical thickness of rings A, B, D and structure of ring B. *Icarus*, 22, 159-174.

French, R.G., et al., 1993. Geometry of the Saturn system from the 3 July 1989 occultation of 28 Sgr and Voyager observations. *Icarus*, 103, 163-214.

Gehrels, T., et al., 1980. Imaging photopolarimeter on Pioneer Saturn. *Science*, 207, 434-439.

Goertz, C.K., and Morfill, G., 1983. A model for the formation of spokes in Saturn's ring. *Icarus*, 53, 219-229.

Green, N.E., 1880. On some changes in the markings of Mars, since the opposition of 1877. *Monthly Notices of the Royal Astronomical Society*, 40, 331-332.

Green, N.E., 1890. Report of the meeting of the British Astronomical Association, Dec. 1890. *Journal of the British Astronomical Association*, 1, 111-114.

Green, N.E., 1897. Reports of the directors of the observing sections, Saturn Section, 1896. *Journal of the British Astronomical Association*, 7, 236-244.

Grün, E., Morfill, G.E., Terrile, R.J., Johnson, T.V., and Schwehm, G., 1983. The evolution of spokes in Saturn's B ring. *Icarus*, 54, 227-252.

Guérin, P., 1970. The new ring of Saturn. *Sky & Telescope*, 40, 88.

Isles, J.E., and Lewis, J. 1990. *Variable Stars*. Enslow, Berkeley Heights (Volume 8 in the Webb Society Deep-Sky Observer's Handbook series).

Lankford, J., 1981. Amateurs versus professionals: The controversy over telescope size in late Victorian science. *Isis*, 72, 11-28.

Marth, A., 1888. Letter to E.S. Holden dated 19 October. Mary Lea Shane Archives of the Lick Observatory, University of California, Santa Cruz.

Marth, A., 1889a. Letter to W.H. Wesley, dated 14 February. Royal Astronomical Society, RAS Letters 1889.

Marth, A., 1889b. On the eclipse of Iapetus by Saturn and its ring-system, on November 1-2, 1889. *Monthly Notices of the Royal Astronomical Society*, 49, 427-429.

Marth, A., 1889c. Letter to W. H. Wesley, dated 12 September. Royal Astronomical Society, RAS Letters 1889.

Marth, A., 1889d. Letter to RAS Library Committee, dated 6 November. Royal Astronomical Society, RAS Letters 1889.

Marth, A., 1890. Letter to E.S. Holden, dated 6 February. Mary Lea Shane Archives of the Lick Observatory, University of California, Santa Cruz.

Maunder, E.W., 1894. Letter to E.E. Barnard dated 2 January. Vanderbilt University Special Collections, E.E. Barnard papers.

McGhee, C.A., French, R.G., Dones, L., Cuzzi, J.N., Salo, H.J., and Danos, R., 2005. HST observations of spokes in Saturn's B ring. *Icarus*, 173, 508-521.

Millis, R.L., 1973. UBV photometry of Iapetus. *Icarus*, 18, 247-252.

Millis, R.L., 1977. UBV photometry of Iapetus: results from five apparitions. *Icarus*, 31, 81-88.

Mitchell, C.J., and Horanyi, M., 2005. Where did the spokes go? American Geophysical Union Spring Meeting 2005, abstract P21C-07.

Mitchell, C.J., Horanyi, M., Havnes, O., and Porco, C.C., 2006. Saturn's spokes: lost and found. *Science*, 311, 1587-1589.

NASA/JPL/Space Science Institute, 2006a. Double-Banded E Ring (PIA 07803). http://ciclops.org/view.php?id=2000 (accessed on 5 July 2006).

NASA/JPL/Space Science Institute, 2006b. Shadow Strands (PIA 08191). http://ciclops.org/view.php?id=1995 (accessed on 2 June 2006).

NASA/JPL/Space Science Institute, 2005a. D Ring Revelations (PIA 07714, 07715). http://ciclops.lpl.arizona.edu/view.php?id=955 (accessed on 18 May 2005).

NASA/JPL/Space Science Institute, 2005b. Fantasy Made Real (PIA 07545). http://ciclops.org/view.php?id=1172 (accessed on 26 August 2005).

Obituary: Albert Marth. *Monthly Notices of the Royal Astronomical Society*, 58, 139-142 (1898).

Obituary: Otto Wilhelm von Struve. *Observatory*, 28, 251 (1905).

Obituary: Arthur Stanley Williams. *Monthly Notices of the Royal Astronomical Society*, 99, 313 (1939).

Osterbrock, D.E., and Cruikshank, D.P., 1983. J.E. Keeler's discovery of a gap in the outer part of the A ring. *Icarus*, 53, 165-173.

Pickering, E.C., 1879. *Annals of Harvard College Observatory, 11, part 2, Photometric Observations*. Cambridge (Mass.), Harvard University Press.

Pickering, E.C., 1882. *A Plan for Securing Observations of the Variable Stars*. Cambridge (Mass.), Harvard Univ. Press.

Pickering, E.C., et al., 1881. Report of the committee on standards of stellar magnitude. *Observatory*, 4, 327-329.

Porco, C.C., 1988. Dual periodicity in the appearance of spokes. *Bulletin of the American Astronomical Society*, 20, 852.

Porco, C.C., and Danielson, G.E., 1982. The periodic variation of spokes in Saturn's rings. *Astronomical Journal*, 87, 826-833.

Porco, C.C., et al., 2005. Cassini imaging science: initial results on Saturn's rings and small satellites. *Science*, 307, 1226-1236.

Robinson, L.J., 1980. Closing in on Saturn. *Sky & Telescope*, 60, 481.

Sandel, B. R., et al., 1982. Extreme ultraviolet observations from the Voyager 2 encounter with Saturn. *Science*, 215, 548-553.

Shapin, S., 1994. *A Social History of Truth*. Chicago, University of Chicago Press.

Sheehan, W., 1988. *Planets & Perception: Telescopic Views and Interpretations, 1609-1909*. Tucson, University of Arizona Press.

Sheehan, W., 1995. *The Immortal Fire Within: The Life and Work of Edward Emerson Barnard*. Cambridge, Cambridge University Press.

Showalter, M.R., 1996. Saturn's D ring in the Voyager images. *Icarus*, 124, 677-689.

Showalter, M.R., 1998. Detection of centimeter-sized meteoroid impact events in Saturn's F ring. *Science*, 282, 1099-1102.

Smith, B.A. 1984. Future observations of planetary rings from groundbased observatories and earth-orbiting satellites. In Greenberg, R., and Brahic, A. (eds.). *Planetary Rings*. Tucson, University of Arizona Press. Pp. 709-710.

Smith, B.A., et al., 1982. A new look at the Saturn system: the Voyager 2 images. *Science*, 215, 504-537.

Spahn, F., et al., 2006. Cassini dust measurements at Enceladus and implications for the origin of the E ring. *Science*, 311, 1416-1418.

Stroobant, P., 1890. Observations de Saturne faites en 1890, à l'observatoire royal de Bruxelles. *Bulletin de L'Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique*, 3rd series, 19, 6, 772-775.

Struve, O.W., 1853. Les dimensions des anneaux de Saturne. *Memoires de l'academie Imperiale des Sciences de St. Petersbourg*. 6 ser.: Sciences mathematiques, physiques et naturelles. 1re ptie: Sciences mathematiques et physiques, T.5. (Memoires de l'academie imperiale des sciences de St. Petersbourg. 6 ser.: Sciences mathematiques, physiques et naturelles; T.7), 439-475.

Terby, F.J.C., 1887. Saturne—compagnon de Sirius. *Observatory*, 10, 163-164.

Trouvelot, E.L., 1877. Physical observations of Saturn. *Monthly Notices of the Royal Astronomical Society*, 37, 191.

U.S. Naval Observatory, Nautical Almanac Office, 1886. *American Ephemeris and Nautical Almanac for the year 1889, Second Edition*. Washington, Bureau of Navigation.

Webb, T.W., 1896. *Celestial Objects for Common Telescopes, Volume 1. Sixth Edition (by T.H.E.C. Espin)*. London, Longmans Green.

James Bryan is a Research Fellow at McDonald Observatory, a branch of the University of Texas at Austin. His research interests include history of astronomy in early Texas, historical observations of the supernova S Andromedae in 1885, and historical visual observations of Saturn's ring system. He is a member of the American Astronomical Society and is a Fellow of the Royal Astronomical Society.