Chapter 2
William Herschel and Comets

Woodruff T. Sullivan III

Introduction

The bulk of what historians have written about William Herschel deals with his ideas on the structure of the Milky Way, as well as on the nature of the nebulae and stellar clusters that he cataloged. His study of Solar System bodies has been particularly neglected, excepting of course his remarkable 1781 discovery of Uranus that permanently changed him from a musician to an astronomer. Yet fully 40% of Herschel's publications in the *Philosophical Transactions of the Royal Society* (hereafter *Phil. Trans.*) were on Solar System topics. Is this corpus just a sideline, of little interest in understanding his grand schemes on the "Construction of the Heavens"? In this article we focus on only a fraction of Herschel's Solar System research, that on comets, and argue that in fact it was importantly connected with his picture of a larger "sidereal universe." Unlike his sister Caroline, William never discovered any *new* comets, but his acute observations of their structure with his superb telescopes, combined with his fertile mind, led to many new ideas.

Herschel was a remarkable natural philosopher in many ways. None of his contemporaries had his peculiar mix of talents. He was not much of a mathematician as were they, had never attended university, and didn't even start doing astronomy until about age 35. He designed and fabricated his own telescopes and within a short time produced instruments of optical precision that were unmatched (for many tasks) by those of men who had spent lifetimes making telescopes. He possessed tremendous energy and drive and cleverness. He enlisted and trained his devoted sister as full-time assistant, thereby increasing his output of observations and scientific papers by at least a factor of two or three from otherwise. And last, but hardly least, he thought about the cosmos in entirely new ways.

W.T. Sullivan III (✉)
Department of Astronomy, University of Washington, Seattle, WA, USA
e-mail: woody@astro.washington.edu

C.J. Cunningham (ed.), *The Scientific Legacy of William Herschel*,
Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-32826-3_2

Why was Herschel interested in comets? First, throughout his career, he was fascinated with any type of *change* in the heavens – variable stars, planetary features, sunspots, variable nebulae. Comets exemplified change *par excellence*. Secondly, discovery and study brought fame, as one's name (or one's sister's name) often became attached to a new comet. Thirdly, comet orbits were very unlike those of planets, whose paths were close to circular and whose directions of rotation and orbital planes showed little variation. Comets not only had extremely non-circular orbits, but were often going "backwards" (retrograde), as well as moving at large angles to the orbital plane of the planets. Where did comets fit into the ever-growing census of Solar System objects? Fourthly, as he emphasized, and unlike most other comet observers, he wanted to focus on the "physical condition" of these strangers, not just their orbits (e. g., Herschel 1808:145). Finally, he was intrigued by their telescopic appearance, sometimes closely resembling many of the thousands of nebulae that he had cataloged and classified – could there be a connection? In fact, he developed a satisfying picture wherein these strange intruders into the inner Solar System were directly linked to the distant nebulae that he knew so well.

For millennia comets had been mysterious visitors to Earth's sky, always unannounced and usually portending doom and gloom (Olson 1985; Yeomans 1991; Schechner Genuth 1997). Their origins and great variety, especially the wondrous tails that always pointed away from the Sun, were puzzling. On the other hand, continually improving application of Newtonian theory throughout the eighteenth century meant that their orbits could be precisely calculated. A comet swooped into the inner Solar System, brightening as it passed closely by the Sun (and Earth), and then disappeared into far outer realms, predicted to return at best in hundreds of years, more often thousands, and sometimes never. The shortest period reliably known during Herschel's time was Halley's Comet, which famously had been demonstrated, upon its predicted return in 1759, to follow an elliptical orbit of period ~76 years.[1,2,3]

[1] The comet's return in 1759, just as Halley had predicted in 1705, was universally viewed as a triumph of Newtonian theory. At that time 20-year-old Herschel had just arrived in England and was scratching out a musician's living with his brother Jacob in London. We have no recollection from him of having seen the comet, even though in May it would have been a notable sight in the evening southern sky. We need to remember that, although London then had no light pollution, it did have heavy smoke; furthermore, Herschel was then a musician, not at all an astronomer.

[2] Comet Halley's following apparition in 1835–1836 was well after William Herschel's death; his sister Caroline, however, saw it at age 85 in October 1835 from Hanover, Germany, and even ~180 years ago she was hampered by light pollution. From her day book:

> Oct 14–15, 1835. I saw the Comet, weather hazy. Gas lights all around me in the Street where I was obliged to go, none of my windows allowing me a prospect of that part of the heavens where the comet was visible. I was however gratified by seeing an object which has for many years been an object of conversation.

Oct 17. Saw the Comet again, very Bright, at Mrs. Beckedorff's Country residence, but very near the horizon.

Caroline's day book is at the Harry Ransom Center, University of Texas (Austin) Herschel Archives (hereafter Texas), 36.12/p5.

In addition, William's son John made detailed observations of the comet from South Africa in January–May 1836.

[3] Edmond Halley also predicted that the Great Comet of 1661 would return in the winter of 1788–1789. Caroline and William searched for this, as did many others, but to no avail. While searching,

Caroline Herschel's Observations of Comets

The eight comets traditionally associated with Caroline Herschel (1750–1848), discovered from 1786 to 1797 (Table 2.1), have been extensively investigated.[4,5] They are briefly discussed here for completeness and for comparison to William's observations, which are also included in the table. But it is important to emphasize that although "her" comets supplied a bit more material for William to study, we have absolutely no evidence that Caroline was ever interested in the types of questions and detailed observations undertaken by William. She focused instead on finding and tracking comets, as did virtually all comet observers of the age.

Using two relatively small, wide-field reflectors designed and built for her by William (her "comet sweepers"), Caroline often scanned the early evening or pre-dawn skies when weather and the needs of William's own observing allowed. Much later (1839, at age 89), when she finally gave one of her sweepers away, she wrote out detailed instructions for its use. They reveal how amazingly well she (and undoubtedly William, too) knew the sky. As you read these instructions (below), be aware that in the sky visible from southern England there are fully 350 fourth magnitude and brighter stars and another 100 Messier objects!

To Sweep For or To Seek Comets
[Caroline Herschel – Oct 1838]

1. *Look over with the naked eye every star of the 1st, 2nd, 3rd and 4th magnitude before you begin to observe with the telescope. In looking them over begin with the Sun as a Center and take every constellation round it at an equal* [angular] *distance that is visible.*
2. *Begin with the telescope in the same manner taking the Constellation*[s] *round the Sun as a Center and begin with those that set first.*
3. *If there has been an interruption of 3 or at most 4 days do not go on with the former series of observations but begin again at No. 1 as if no observation had been made at all.*

Requisites

1. *The name of every star as far as the 1st, 2nd, 3rd and 4th magnitude must be known at sight.*
2. *Every Nebula in* [Messier's catalog] *must be known so well as to be found in the Sweeper in one minute.*[6]

---

however, Caroline discovered her second comet.

[4] Olson and Pasachoff 1998; Hughes 1999; Hoskin 2005 (the most complete study); Hoskin 2013; Hoskin 2014.

[5] The span of dates for Caroline's comet discoveries was driven by personal circumstances. As Hoskin has emphasized, seven of her eight discoveries took place between (a) William's marriage in May 1788, which meant that *his* observing time greatly shrunk and thus her labor as assistant was less needed, and (b) her moving to a separate apartment in late 1797, making sweeping for comets far less convenient.

[6] Bullard (1988:146, Hoskin 2005:382, 390).

Table 2.1 Comets observed by William & Caroline Herschel

Year	Name	CH #	CH & WH Obsns	Comments	Paper / Source
1781	[Georgium Sidus = Uranus]		13 Mar 1781+	Identified as a new planet only after 6-12 months; Paper entitled "Account of a comet"	WH (1781)
+++++	++++++++++++++++++++++++	+++	++++++++++++++	+++	+++++++
1781 II	C/1781 T1 Méchain		21–23 Nov		WH (1802a:195)
1783	D/1783 W1 Pigott		29 Nov – 13 Dec		WH (1802a:195)
1786 II	C/1786 P1 C. Herschel	#1	1 Aug – 26 Oct	Discovered while WH in Germany, using new sweeper built by him for her	CH (1787), WH (1787a)
1787	C/1787 G1 Méchain		19 Apr		WH (1787b:232)
1788 II	35P/1788 Y1 C. Herschel – Rigollet	#2	21–22 Dec	1939 – recovered and found to be periodic (155 yr) by Roger Rigollet	WH (1789) (reports CH obsns)
1790 I	C/1790 A1 C. Herschel	#3	7–10 Jan	Seen only twice by CH, but confirmed 12 days later by Charles Messier; Fig. 1	RAS C.1/1.2/p56=i8
1790 II	8P/1790 A2 Tuttle (Méchain originally)		18 Jan	1858 – identified as periodic (13.6 yr) by Horace Tuttle	WH (1802a:196)
1790 III	C/1790 H1 C. Herschel	#4	17 Apr – 29 Jun	WH out of town	Letter to RS (unpub.) RS L&P.IX.180
1792 I	C/1791 X1 C. Herschel	#5	15 Dec 1791 – 13 Jan 1792	Confirmed by WH on discovery night with 7 ft & 20 ft telescopes	WH (1792) (reports CH obsns)
1792 II	C/1793 A1 Gregory		13 Jan – 7 Feb 1793	naked eye	
1793 I	C/1793 S2 Messier	#6	7–8 Oct	Observed 10 days after Messier's discovery	CH (1794)
1795 VI	2P/1795 V1 Encke (C. Herschel originally)	#7	7–28 Nov	Naked eye 1818 – identified as periodic (3.3 yr) by Johann Encke	CH & WH (1796)
1797	C/1797 P1 Bouvard – C. Herschel	#8	14–28 Aug	Discovered (naked eye) by CH & Alexis Bouvard (and others) on the same evening; WH out of town; CH rides horse ~30 miles to Greenwich to report comet	RAS C.1/1.1&1.2/ pp91-6
1799 I	C/1799 P1 Méchain		8 Sep – 4 Oct		WH (1802a:196)

1806 I	3D/1805 V1 Biela		8–9 Dec 1805	WH: "I discovered a comet"–but 4 weeks after Jean Louis Pons; 1826 – identified as periodic (6.6 yr) by Wilhelm von Biela; Fig. 3	RAS W.3/1.12/ p16=i10 (Dreyer 1912:cxi)
1806 II	C/1806 V1 Pons		27 Jan – 1 Feb 1807	CH learned of it via a German newspaper	WH (1807)
1807	C/1807 R1 Great Comet of 1807		2 Oct 1807 – 21 Feb 1808	Naked eye; 47-night observing campaign; Fig. 4	WH (1808)
1811 I	C/1811 F1 Great Comet of 1811		2 Sep 1811 – 2 Jan 1812	Naked eye; 33-night observing campaign; Figs. 5, 6, 7	WH (1812a)
1811 II	C/1811 W1 Pons		1–20 Jan 1812	Naked eye	WH (1812b)
1815	13P/1815 E1 Olbers		29–31 Mar	Learned of it via a newspaper; 1887 – identified as periodic	RAS C.1/1.3/ p110=i12
1819 II	C/1819 N1 Tralles Great Comet of 1819		3–22 Jul	Naked eye	RAS W.1/8.43/i137 RAS W.2/2.8/p22=i24
+++++	+++++++++++++++++++++++	+++	+++++++++++++	+++++++++++++++++++++++++++++++++++++++	+++++++
1823	C/1823 Y1 Great Comet of 1823		31 Jan 1824	CH – in Hanover	RAS C.1/1.3/ p111=i12
1835 III	1P/1835 P1 Halley		14–17 Oct	CH (age 85) – in Hanover	Texas 36.12/p5

CH Caroline Herschel; *WH* William Herschel

"Year" column contains the former convention (before 1995) for naming comets; "Name" column follows current convention

Start and end dates of "Obsns," as well as "Paper / Sources," refer only to CH and WH's observations and papers; the span of observing dates is based on perusing various observing logs, in particular those in RAS C.1 and RAS W.3/1

CH's 8 comets are numbered. Six still bear her name as discoverer; one had already been discovered; and one was named much later after Johann Encke, who first demonstrated it to be periodic

Primary sources: RAS Archives; Kronk (1999)

Her first comet in 1786 was greeted with joy by the Astronomer Royal, Nevil Maskelyne, in a letter to William:

> *I am happy in the expectation your sister gives me both of her discovering more comets and favoring me with immediate notice of them. I hope we shall by our united endeavors get this branch of astronomical business from the French, by seeing comets sooner and observing them later.*
>
> *Your continual attention to the heavens under their own canopy, without the glare of lights in a room, added to the superior excellence of your telescope, must give you great advantages in discovering and pursuing comets.*[7]

Caroline's persistence (e.g., she searched on and off for 3 years before finding her first), excellent eyesight, stamina, and intimate knowledge of the sky led altogether to the discovery of eight comets of which she had no prior knowledge. She gained fame as the lady comet hunter (Fig. 2.1). Most of her comets were sixth to eighth magnitude, except for the last one, a very bright third magnitude which she found in 1797 while making her routine naked-eye reconnaissance (see the instructions above) at the start of an observing session (Hughes 1999). After this particular discovery, a full night of observing, and only a short nap, she took no chances to lose her priority of discovery. At age 47 and less than 5 ft (152 cm) in height, she rode horseback 27 miles (44 km) to Greenwich, and exhaustedly reported the comet to Maskelyne in person![8]

Of Caroline's eight comets, only one had been discovered before (1793 I) and another was renamed for Johann Encke when much later he established it as a recurring comet with a period of 3.3 years. That leaves six comets with her name attached to this day. Once she had found a comet, she and William would pounce on it as much as weather and the comet's brightness allowed. Campaigns lasted for as long as 4 months (Table 2.1).

With regard to publication, only three of her comets were published under her own name (in brief reports), although note that she was the first woman to *ever* publish in *Phil. Trans.,* and no one would arrive in second place until Mary Somerville in 1826. Discovery details of two other of her comets were given in papers by William. For another (1790 III) she sent a letter to the Royal Society, but for some reason it was never published. Finally, results on two other comets were never reported. One was observed on only one night and the other for two weeks.

---

[7] Maskelyne:W. Herschel, 25 Oct 1786, Royal Astronomical Society (London) Herschel Archives (hereafter RAS) W.1/13.1/m30 = i891-2. (A notation such as "p22" refers to page 22 of the original Ms. (where numbered). Often more convenient is the "image number" indicated here by "i24", referring to PDF image number 24 on the set of three available DVD's containing the entire RAS Herschel Archives.) Maskelyne is referring here to the Herschels' technique of usually observing in complete darkness in the open air, resorting only rarely to dim light for jotting notes. The Greenwich refractors were apparently kept inside a partially lit room.

[8] C. Herschel:Joseph Banks, 17 Aug 1797, RAS C.1/3.8/i3.

Fig. 2.1 "The Female Philosopher smelling out the Comet" by R. Hawkins(?) (1790). The cartoon does not mention Caroline Herschel, but it seems certain that it refers to her; by the end of 1790 she had discovered four comets and was becoming well known to the educated public. The woman says "What a Strong Sulpherous scent proseeds from this meteor" as she observes a comet with a baby emitting gas from its bottom. The term "meteor" had long referred to any sort of phenomenon taken to arise in Earth's atmosphere (e.g., lightning, shooting stars, and aurorae); until the seventeenth century this included comets (Pierpont Morgan Library/Art Resource, New York City. Used with permission)

William Herschel's Observations of Comets

The late eighteenth century saw a rapid increase in seeking and observing comets. The French astronomer Charles Messier was the first to systematically scan the sky for a new comet night after night (he was called "the comet ferret"), and from 1760 to 1800 he and his compatriot André Méchain dominated the field. In the period 1781–1799, in which Caroline and William Herschel were most actively observing, there were 25 appearances of comets; of those Messier and Méchain discovered ten and Caroline was in third place with six (Hughes 1999:82). Of those 25 comets, the Herschels observed 14, as well as 7 more after 1799 (Table 2.1). Of the 22 papers published on comets during the period 1780–1822 in *Phil. Trans.*, fully 60% (13) were by either Caroline (3) or William (10).[9] During William's early observing days in Bath (when his fulltime "day job" was as a musician) there were three comets that came into the British skies that he might have seen, but none were entered into his observing log from 1774 until his first on Nov 22, 1781.[10] Of course Herschel was a relatively novice observer at that time and in any case not purposely looking for comets; nor was he tied into the network of astronomers who immediately notified each other of new comets.

At first it seems puzzling that William, despite his thousands of hours at the telescope, never managed to be first to find a comet, whereas Caroline discovered so many. There are two main reasons for this. The first is that William set up a division of labor whereby Caroline searched for comets only whenever she was not needed to assist William (indispensably) with his own varied observations. She also could observe when William was away on business or (after he married) on holiday; in fact three of her discoveries came when William was away. As in her instructions given in the previous section, she searched by methodically and quickly scanning the sky for a faint, fuzzy object near the just-set Sun in the evening twilight or the about-to-rise Sun in the morning. With a candidate in hand, she then tracked the object as long as possible to check whether it shifted its position with respect to the pattern of background stars; several hours of tracking were a minimum – night-to-night was much better. If it shifted, it was a comet; if not, it was a nebula located well outside the Solar System, also interesting but not the jackpot. Thus Caroline could search for 1–2 hours in the evening or morning twilight, when the sky was not absolutely dark, as William required to study his extremely faint objects.

Although comets can sometimes be found well away from the Sun (and Caroline searched for these, too, when she could), William was at a disadvantage to come upon a comet while sweeping for nebulae because his field of view (typically 15′)

[9] The listing of all *Phil. Trans.* papers on comets (and meteors) is given in Appendix 1 of Olson and Pasachoff (1998). The number of papers on comets peaks in the 1750–1800 period.

[10] In addition, we should not forget Herschel's most prominent "cometary" episode, early in his career. On the evening of 13 Mar 1781, he discovered a non-stellar object and tracked it for months, arguing in many publications and letters that it was a comet. Eventually others worked out a circular orbit and disagreed – the Solar System had acquired a new planet (Uranus) well outside Saturn. The discovery paper of 1781 is entitled "Account of a comet."

was much smaller than Caroline's (about 2°). Not only that, he had a far slower pace of sweeping than Caroline. With his telescope fixed on the meridian, he swept at ≤15° per hour, the rotation rate of Earth, whereas she zipped through the sky at ~10° *per minute*.[11] Furthermore, once William found a candidate nebula by sweeping, he typically did not check it again for weeks or months, far too long to confirm a new comet and announce it to the world. In fact roughly 70% of his cataloged nebulae ended up *never* being observed a second time – for these nothing was known about any possible non-sidereal motion. In one of his comet papers Herschel (1808:159) remarked that it would be a fascinating exercise ("were it not a task of many years labor") to re-check all of his cataloged nebulae and see if any of them were entirely "missing," i.e., had moved away from their position decades before.[12]

If he'd seen an obvious tail on any new object, he certainly would have stopped his routine and looked at it with other, smaller telescopes, but comets often don't exhibit tails, especially when first discovered. In fact, Herschel's classification scheme for his cataloged nebulae and star clusters (2,500 in all), based on their morphology to his skilled eye, even included the rubric "cometic nebulae" (Herschel 1786:469, 1811:306),[13] which resembled tail-less comets (although almost always *much* fainter) in having a faint halo surrounding a relatively bright center and "round figure" (in comets then and now called the head, or *coma*, from the Latin for "hair") (see Fig. 2.2). For example, Herschel noted that the Great Comet of 1807 would have fit nicely amidst descriptions of his cataloged nebulae when on Dec 16, 1807, he described it as a "very bright, large, irregular, round nebula, very gradually much brighter in the middle, with a faint nebulosity on the south preceding [southwest] side." (Herschel 1808:153–4) The sole discriminant between a nebula and comet was that the former's description and location remained stable, whereas the latter's changed dramatically as the weeks passed.

While sweeping the heavens Herschel did have a few puzzling cases where he suspected an encounter of the comet kind, but none panned out to a verifiable discovery:

> **5 Aug 1782**. Shortly after moving from Bath to Datchet (near Windsor Castle) he thought he'd found a new comet, but after several nights of study realized that it was No. 5 in Charles Messier's recent catalog of bright nebulae and star clusters [Dreyer 1912:xxxvii].[14]

[11] Hughes (1999:79–80) and Hoskin (2005:405), citing a letter in RAS Nathaniel Pigott, Maskelyne:Pigott, 6 Dec 1793.

[12] My rough estimate of ~70% of William's 2300 nebulae observed only once comes from a perusal of Herschel's published listings (excluding his clusters). For his Class III ("faint nebulae"), the fraction is much higher at ~90%. But despite this, Steinicke's (2010:32) exhaustive analysis of Herschel's catalogs concludes that only five of his nebulae cannot be found today at their reported positions. Might one of these five have been a comet? These results confirm that Herschel made a wise decision not to spend time checking all of his once-only nebulae to see if they might have been in fact comets.

[13] About 1% of Herschel's nebulae were classified "cometic."

[14] Herschel's confusion over whether some of his new nebulous objects might be comets shows how difficult it was to tell the two categories apart without multi-night observations. This in fact was precisely the reason that Messier had published his listing of nebulous objects; he wanted to

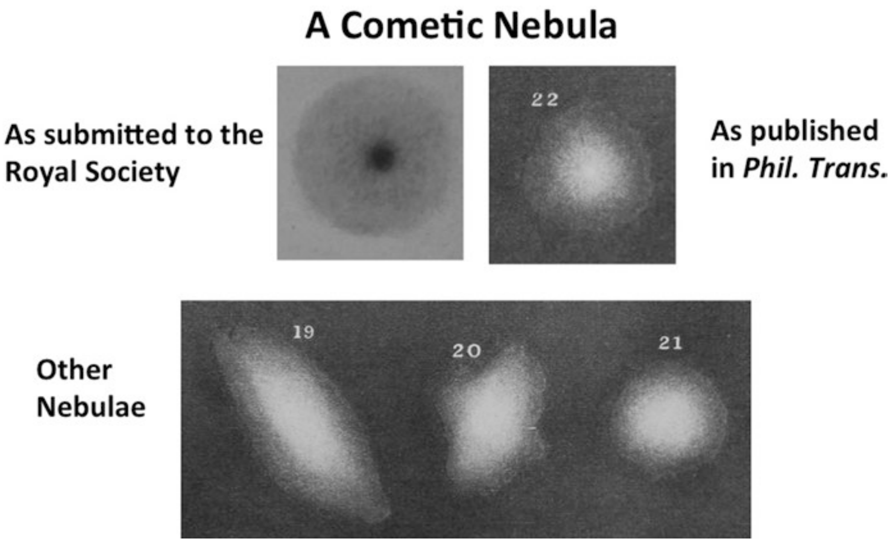


Fig. 2.2 Drawings illustrating Herschel's class of "cometic nebulae." The top pair are different versions of the same drawing (of catalog number H I.4 first observed on 19 Dec, 1783), as submitted for publication and as finally appearing in *Phil. Trans.* Note the significant difference in appearance. The *bottom row* shows other types of nebulae for comparison (Numbered drawings from Herschel 1811; *top left* drawing from Royal Society PT.5.16. Used with permission)

18 Dec 1783. In his first catalog of 1,000 nebulae, he says that he saw a "cometic" nebula, but could never find it again (Herschel 1786:498; Dreyer 1912:294-5). Steinicke, however, says that Herschel must have made a mistake when checking, because Herschel's object can today be identified reliably with the galaxy NGC 1055.[15]

Jan 23, 1784. He again "lost" a bright nebula, but many years later deduced that wrongly measured positions meant that he didn't recognize it as a Messier object (No. 49). (Herschel 1786, 498; Dreyer 1912: 294–5)

Dec 8, 1805. He finally did "discover" a comet (Fig. 2.3) and promptly sent notice to the Royal Society, but, as with Caroline's sixth comet in 1793, it turned out that it had been already found, by Jean Louis Pons (Marseille) four weeks before (Dreyer 1912:cxi).

Herschel's first four papers on comets, from 1787 to 1796, were relatively brief reports on the comet *du jour*, providing mainly descriptions of how the comet's appearance had changed as it moved along its orbit. Sometimes he also provided rough sky coordinates, but these were awkwardly given and wanting in accuracy, for example: "about 42′ north of 22 Cygni, in a line continued from 21 (η) through 22

make life easier for comet hunters by establishing a reliable "nuisance list" of potentially misleading objects bright enough to be visible in small telescopes.

[15] W. Steinicke, Historical Catalogue of William Herschel Nebulae and Star Clusters. www.klima-luft.de/steinicke (accessed Nov 2016).

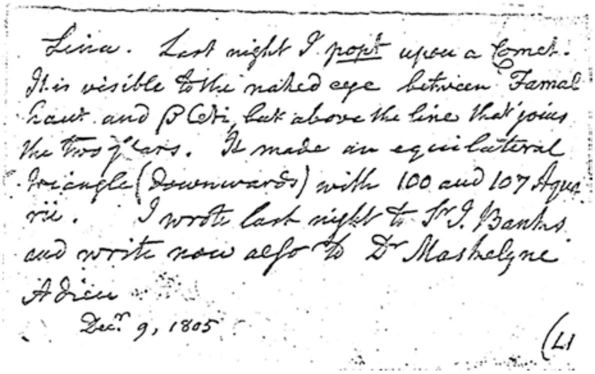

Lina. Last night I popt upon a Comet. It is visible to the naked eye between Famal haut and β Ceti, but above the line that joins the two stars. It made an equilateral triangle (downwards) with 100 and 107 Aqua rii. I wrote last night to Sr J. Banks and write now also to Dr Maskelyne Adieu
Decr 9, 1805
(41

Fig. 2.3 Note from William Herschel to his sister Caroline on 9 Dec 1805. "Lina. Last night I popt [popped] upon a Comet. It is visible to the naked eye between Fomalhaut and β Ceti, but above the line that joins the two stars. It made an equilateral triangle (downwards) with 100 and 107 Aquarii. I wrote last night to Sir J. Banks [President of the Royal Society] and write now also to Dr. Maskelyne [Astronomer Royal]. Adieu." (RAS W.1/8.23/i81)

nearly; it is not quite come to the line…" (Herschel and Herschel 1796:133) This kind of description was the best he could do because his expertise was *not* in properly measuring accurate right ascensions and declinations as with the carefully mounted and calibrated refractors that dominated his era, such as at Oxford University and Greenwich Observatory. Although the latter were superb for producing accurate positions of celestial objects, they were inferior to Herschel's reflectors in many other ways, such as in studying faint objects. Another striking difference was that Herschel's mathematical skills were severely limited compared to many of his colleagues, who were as much mathematicians as astronomers. This meant, for instance, that Herschel never in his career calculated an orbit based on measures of comet positions.[16]

With the new century, Herschel began to study comets more seriously, advancing detailed ideas in four more papers (1802–1812) on their origin, how they changed with time, their forms, etc. He may well have been inspired to think more about the Solar System by Giuseppe Piazzi's discovery in 1801 of the first asteroid (Ceres), taken to be a new planet between Mars and Jupiter and hailed as a first-class discovery not unlike Herschel's two decades earlier (Cunningham 2016a, b). Furthermore, two bright and long-lasting comets appeared in the skies, allowing detailed observations. Finally, his core project of sweeping the northern sky for faint nebulae and star clusters had come to a close, as at this time he published the final installment of his catalog of 2500 objects. (Herschel 1802b).

In a paper primarily addressing the nature of the new asteroids (a second one – Pallas – had just been found), Herschel (1802a) drew up a list of the properties of

[16] In the RAS Herschel archives is an undated document (no source given) in which Herschel lays out the many complicated steps to determine the parameters of a comet's orbit, given a few observed positions. But there is no extant evidence that he ever carried out such a calculation. (RAS W.3/39.2/pp48-52 = i28-32).

planets and comets, and wondered where asteroids might fit in. Arguing that they fit somewhere in between, he saw the need for a distinctive new name.[17] But he also pointed out that maybe an asteroid is nothing more than a comet far removed from the Sun.[18] In fact maybe "comets, asteroids, and even planets might possibly be the same sort of celestial bodies under different circumstances" (Herschel 1802a:231). Here he was characteristically thinking about changes of astronomical objects over long timespans, something he had repeatedly done from his earliest days of observation. Back in 1781, 8 months after he first sighted the "comet" whose nature was still being debated but which would be soon recognized as a new outer planet, he wrote to Joseph Banks at the Royal Society:

> [This] *may give room to suspect that a Body is now exposed to the attention of Philosophers, which may prove to be either a new Planet or perhaps a Star that may partake both of the nature of Comets and Planets; and be, as it were, a Link between the Cometary and Planetary Systems, uniting them together by that admirable connection already discovered in so many other parts of the creation....*[In the future we will] *obtain a still more extended view of the wonderful order that reigns throughout the whole Solar and Sidereal System.*[19]

The Great Comets of 1807 and 1811

In the early nineteenth century, with Herschel in his 60s, two "Great Comets" excited both the public and astronomers. The first was the Great Comet of 1807 (Fig. 2.4). Its brightness and pathway through the sky allowed him to observe it for 47 nights over 5 months in the winter of 1807–1808. He was intensely interested in whether a distinct, small nucleus could be discerned at the center of the comet's bright head – the compact object presumed to exist by astronomers. In only two of sixteen of his previously observed comets had he seen a "very ill defined small central light" (Herschel 1807:266). But now this larger and brighter 1807 comet had allowed him to establish to his satisfaction the existence of a tiny nucleus, which he emphasized could only be achieved because of his superior telescopes:

> *The truth is that inferior telescopes, which cannot show the real nucleus, will give a certain magnitude [size] of the comet, which may be called its head….No telescope, but what has light and power in an eminent degree, will show it distinctly.* (Herschel 1808:146)

---

[17] Herschel's support for the term *asteroid*, which first appeared in print in Herschel (1802a:228), led to its eventual adoption by the astronomical community. The story of the naming is given in detail in Cunningham (2016a).

Searching for new asteroids himself, Herschel made a few sweeps within the ecliptic plane, but came up empty-handed.

[18] In 1785 Herschel had also considered the possibility that his nebulae of Class IV (coined "planetary nebulae") might actually be comets far from the sun. But he decided not, based on their large inferred brightness and size if at that distance compared to comets near the Earth and sun, when one would expect the opposite effect (Herschel 1785:265).

[19] Herschel:J. Banks, 19 Nov 1781, RAS W.1/7.

Fig. 2.4 "John Bull making observations on the Comet" (Thomas Rowlandson etching, 1807). John Bull (Great Britain) observes the threatening Great Comet of 1807 (Napoleon) across the English Channel, with King George III as the Sun. "Aye..Aye..Master Comet – you may attempt your Periheliums – or your Devilheliums for what I care but take the word of an Old Man you'll never reach the Sun [Great Britain] depend upon it." (Bodleian Libraries, University of Oxford, Wikimedia Commons)

He went to great pains to measure its diameter despite his inability to employ his usual wire micrometer (used on double star separations, for instance) because high magnifications necessary to measure a small object did not work well when the object was also extended. Instead, he resorted to an unconventional technique. As a calibration, during the day before his night of observations, he viewed through his telescope three "globules" of sealing wax perched on top of a post measured to be precisely 2422 inches (~60 m) away. He was trying to fix in his head exactly how large a certain known angular size appeared in the eyepiece's field of view, so that in the night-time he could estimate *from memory* that the comet's nucleus was, say, 1.5 times his smallest globule (diameter 0.0290 inch, or 0.74 mm), which subtended an angle of 2.47″. For instance, using a magnifying power of 221 on one night with his reflector of 10 ft (3.0 m) focal distance, he measured a nucleus diameter of 2.5–2.6″. In this manner Herschel observed with several of his telescopes (including his 20-ft reflector), at various magnifications, and concluded that the nucleus diameter was less than 2.5″. In the end, however, he put more trust in views on a fine night through his 10-ft telescope when he could compare the nucleus's angular size with that of Jupiter's moon Ganymede, known to be ~1.5″. He finally settled on a figure of 1.0″; then knowing the distance to the comet, he calculated the "real diameter of the comet" as 538[20] miles (870 km) (Herschel 1808:156).

Herschel next used his observation that the small disk was always uniform and circular to infer that the comet was "self-luminous," i.e., not shining by reflected light. (He optimistically felt his telescope and eye were able to discern object sizes and features as small as a few tenths of an arcsecond – see the following section.) He did this by working out the Earth-comet-Sun angle and therefore the expected phase and shape of the comet if it were a sphere shining solely by reflected light as does our Moon. Since he never observed the expected gibbous shape for the comet nucleus,[21] reflected light was not the answer. Final conclusion: the nucleus was planet-like with a "condensed or solid body," but unlike a planet it was self-luminous (Herschel 1808:155).[22]

Herschel was less certain of the nature of the light seen in the coma and tail. He noted that many times he saw stars disappear behind the comet, but perhaps that was due to either blockage by reflecting "floating particles," or to blending in the glow of self-luminous matter. But then he invoked Okham's razor to argue against the supposed particles: "We ought certainly not to ascribe an effect to an hypothetical cause, when the existence of one [cause], quite sufficient to explain the phenomenon, is evident." (Herschel 1808:158).[23]

In the end he favored a tail of "radiant matter," perhaps like the aurora borealis.

The second Great Comet came in 1811 and took Europe by storm (Fig. 2.5). It was visible to telescopes for 17 months and to the naked eye for 9 months (a record not broken until Comet Hale-Bopp in 1997). Called "Napoleon's Comet"(also see Fig. 2.4) because its bright head and long, branched tail were taken to have presaged his ill-fated invasion of Russia in 1812, Tolstoy even used it in the plot of *War and Peace*.[24] Starting in September 1811 Herschel observed this comet on 33 nights over 4 months of British weather, employing his naked-eye, a low-power "night glass," and an arsenal of four large telescopes; this allowed him a variety of eyepieces (changing magnifications and fields of view) and ratio of focal distance to mirror diameter (f/d ratio, affecting sensitivity to brightness levels and visibility of struc-

[20] Significant figures apparently were a concept unknown to Herschel and his contemporaries.

[21] His calculated phases had the object's illuminated diameter ~20–25% less in one direction than the other. His observations to look for this, as well as his uncertainties, are discussed in the following section".

[22] Herschel also reported colors, but never used them in his interpretations. For example: "The colour of [the nucleus] was nearly white inclining to red, resembling the brilliancy of a coal in the fire when it is nearly as white as it can be, but not so white as Iron when it is in a welding heat." (RAS W.3/1.12/p24 = i14).

[23] Newton, at the start of his Principia, had listed as one of the four "Rules of Reasoning in Natural Philosophy": "To the same natural effects we must, as far as possible, assign the same causes."

[24] Book 8, end of Chap. 22, where it is confusingly referred to as the "comet of 1812." I have not been able to find any source reliably reporting that Napoleon *himself* viewed it as "his" comet, but certainly other persons did, portending good or bad depending on their nationality. In 1808 Napoleon was undoubtedly pleased when Messier pointed out that the Emperor's birth coincided with the appearance of a bright comet in 1769 (Schechner Genuth 1987:54).

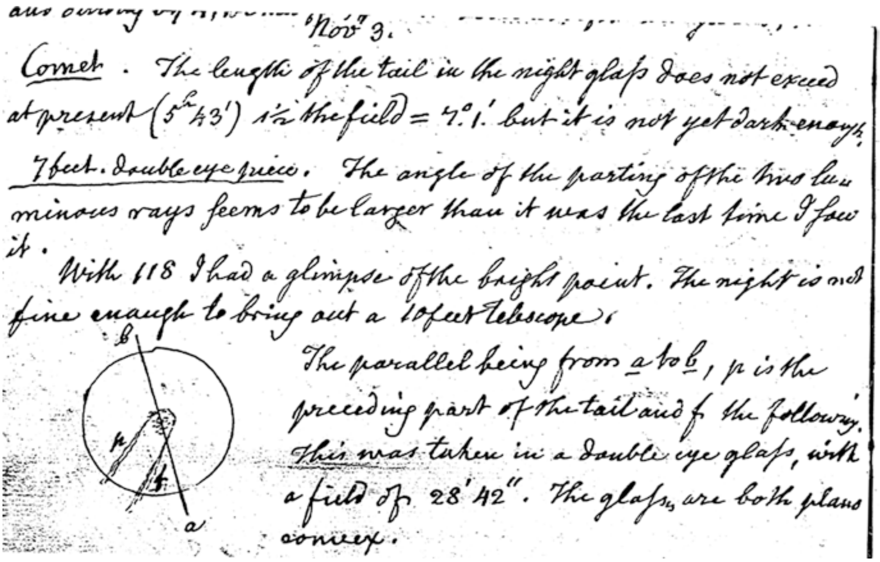
Fig. 2.5 The Great Comet of 1811 "as seen at Daybreak the 15th October from Otterbourne Hill, near Winchester." Engraving by A. Pether, 1814 (Wellcome Library, London. Used with permission)

tures). He monitored how the structure of the comet's nucleus, coma and tail continually changed, and submitted a paper to *Phil. Trans.* even before the comet had left the skies. Although Herschel (1812a) devoted fully 18 pages to intricate descriptions, it is amazing that he offered readers not a single drawing of the comet.

His logbook too contains only *one* drawing (Fig. 2.6) to accompany ~2000 words of description! In order to aid discussion of the many aspects of the comet to which Herschel called attention, Fig. 2.7 attempts to fairly represent his words.[25]

Herschel's paper first presents his observations, followed by his interpretation, entitled "the *real* construction of the comet" (italics mine). In this he was paralleling his lifelong project of mapping out and deducing the *three-dimensional* shape of our stellar system, an endeavor he called "the construction of the heavens." Just as for the Great Comet of 1807, he was convinced that the combination of his skilled eye and his superior large telescopes (including the 20-ft (6.1-m) reflector) with high-power eyepieces (as much as 600×) could discern a tiny "planetary body" manifesting as an "extremely small bright round point, entirely distinct from the surrounding glare" (Herschel 1812a, p. 116). Employing the same globs of sealing wax as in 1807, he measured this planetary body to have a diameter of 0.775″, or 428 miles (690 km). He argued, along the same lines as for the 1807 comet, that he could

[25] If Herschel had published such a drawing as Fig. 2.7, in subsequent decades it would have become *the* standard to illustrate what a bright comet looks like; not until mid-nineteenth century did such detailed drawings finally appear. It is surprising that he did not seize this opportunity.



Nov 3.

Comet. The length of the tail in the night glass does not exceed at present ($5^h 43'$) 1½ the field = 7°.1. but it is not yet dark enough.

7 feet. double eye piece. The angle of the parting of the two luminous rays seems to be larger than it was the last time I saw it.

With 118 I had a glimpse of the bright point. The night is not fine enough to bring out a 10 feet telescope.

The parallel being from a to b, p is the preceding part of the tail and f the following. This was taken in a double eye glass, with a field of 28′42″. The glasses are both plano convex.

Fig. 2.6 William Herschel's observing log (in his hand) for 3 Nov 1811. This is his only drawing of the Great Comet of 1811. The circle defines the field of view of 29′ on his 7-ft telescope at magnifying power of 118. The labels and line indicate orientation of the comet on the sky. RAS W.2/2.8/p8v = i11

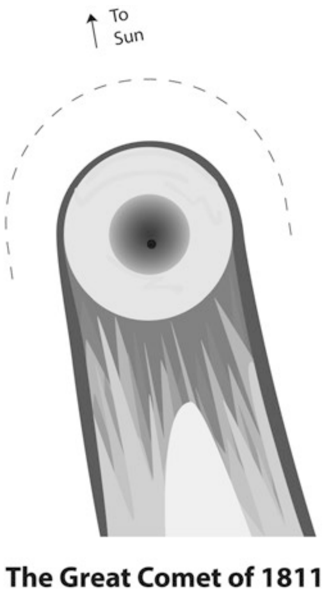


Fig. 2.7 Author's drawing of the Great Comet of 1811, based on the detailed description by William Herschel (1812a). The drawing is a "negative," meaning that dark areas here were bright against the night sky, and light areas were dark. The small dot (slightly off-center) is the nucleus or central "planetary body." It is surrounded by the "head" of size 4′. The head is surrounded by an empty gap, which Herschel called the "transparent cometic atmosphere"; this gap is bounded by the thin bright "envelope," which wraps around the head and defines the outer edges of the tail. The "transparent cometic atmosphere" is presumed to extend indefinitely (and invisibly) outside the envelope (indicated in the drawing by the dashed circle). The tail extends far off the edge of the drawing (Drawing by Woodruff Sullivan)

discern that the object was truly round (i.e., showed no phase effect – see later) and therefore it shone by emitted rays rather than reflected. Around this bright central object was a circular region of uniform brightness which he called the "head," about 3–4′ in size, or 125,000 miles (205,000 km).

The head was the atmosphere of the central planetary body, just as the planets and the Sun (also considered to be a planet) had atmospheres; indeed, the structure of the comet's atmosphere bore strong resemblances to his two-decades-old model for the solar atmosphere (Herschel 1795:58–62).[26] Continuing outwards like nested Russian dolls, next was a dark "transparent cometic atmosphere," as large as 15′ or 500,000 miles (800,000 km) in diameter. He took it as transparent because one time the motion of the comet took it across three stars that suffered no diminution. It was also "elastic" because only a responsive gas would take on such a rounded form under the influence of gravity. This atmosphere was surrounded by a thin, bright "envelope" that was semi-circular on the sunward side and continued outwards on the anti-Sun side, defining the outer edge of the comet's tail. Herschel's greatest reported length for the tail was ~25°, which worked out to be far greater than the Earth-Sun distance. As the months passed, he saw the tail split in two, become curved and asymmetric, and change in width. He closely compared the nebulosity of the tail with that of the Milky Way and of the Orion Nebula, finding all of them to be "perfectly alike." He was struck by how all of the cometary components slowly disappeared as the comet moved away from the Sun, and concluded:

> *I had reason to suppose that all the still visible cometic phenomena of planetary body, head, atmosphere envelope, and tail, would soon be reduced to the semblance of a common globular nebula; not from the increase of the distance of the comet, which could only occasion an alteration in the apparent magnitude of the several parts, but by the actual physical changes which I observed in the construction of the comet.* (p. 127)

Here he directly compared the appearance of the weakened comet with one of the classifications of nebula that he had instituted, namely the "globular" type, which looked roundish and sometimes broke up into stars with a larger telescope.[27]

In the interpretive part of the paper, he argued that the planetary body, head and transparent cometic atmosphere were all actually spherical[28] because (1) gravity tends to make a spherical object (as Newton had shown), and (2) he had seen the comet at many different angles over the months, and "based on the doctrine of chances" their always-round appearance made a spherical volume very likely (p. 133). On the other hand, the tail material was in a hollow cone with a hemispherical cap toward the Sun – the tail's bright edges (the envelope) were simply a projection effect as one looked through a greater amount of luminous material. The light from

---

[26] Jean-André Deluc (1809), who visited Herschel several times, had earlier published identical ideas. Herschel (1812a:119) did cite Deluc (1809) for another aspect of comet structure, but not for this.

[27] Herschel (1785:218) had coined the term "globular cluster" much earlier.

[28] However, Herschel had also observed (p. 121) a slight sunward shift of the center of the comet's head and atmosphere relative to the planetary body (see Fig. 2.7). This he ascribed to a preferential heating and dilation of the atmosphere on the sun side.

the comet was "phosphoric" (self-emitting), a result of the Sun acting on the atmosphere, causing the cometic matter to expand and decompose. This seemed reasonable because it was well known that solar rays can produce all sorts of "light, heat and chemical effects."

Herschel imagined that the planetary body's initial transparent atmosphere extended well outside the visible envelope (Fig. 2.7). As the comet approached the Sun, vapors rose within the sunward side of the atmosphere and became rarefied and (for some unstated reason) finally came to a certain level where they remained suspended and formed the observed envelope. This envelope/layer was initially only on the sunward side, but:

> *If we suppose the attenuation and decomposition of this matter to be carried on till its particles are sufficiently minute to receive a slow motion from the impulse of the solar beams, then will they gradually recede from the hemisphere exposed to the sun, and ascend in a very moderately diverging direction towards the regions of the fixed stars* [away from the Sun]. (p. 138)

Herschel was essentially saying that pressure from sunlight on small particles caused their shining envelope/layer to wrap around to the anti-Sun side of the comet and eventually form the tail, which became more rarefied and fainter as it moved away from the planetary body. Finally, he suggested that the whole comet might be rotating just as planets do, which would explain various observed asymmetries in the envelope and tail if the planetary body or its atmosphere had inherent non-uniformities (pp. 139–40).

Herschel's next step boldly linked the marvels of comets to the "immensity of the nebulous matter, which I have shown to exist in the heavens" (p. 140). Here he was of course referring to the thousands of nebulae, all well outside our Solar System, that he had discovered and categorized over his career. Might it not be that comets and his nebulae were different manifestations of the same object? Perhaps one was a younger version, and eventually morphed into the other? Or did they change back and forth, depending on where they were located? The Newtonian orbits calculated for almost every comet were very close to parabolas, meaning that they likely traveled in regions far outside the orbit of Uranus (or rather, the Georgium Sidus). Comets, then, might provide major clues to the nature of his nebulae. In fact in a previous paper about these nebulae published just 6 months before, Herschel had (as mentioned above) described a type of nebula called *cometic*:

> *Their great resemblance to telescopic comets, however, is very apt to suggest the idea, that possibly such small telescopic comets as often visit our neighbourhood may be composed of nebulous matter, or may in fact be such highly condensed nebulae.* (Herschel 1811:306)

Herschel devised a grand scheme (illustrated in Fig. 2.8) in which a comet far from the Sun was a small planetary body[29] surrounded by a very large tenuous atmosphere (the transparent cometic atmosphere). This stage was represented by one of

[29] Although Herschel had seen evidence for a nucleus in only 4 of 18 observed comets, he apparently felt that the visible nuclei of the much larger 1807 and 1811 comets inferred that *all* comets had central planetary bodies, but were often too small to discern.

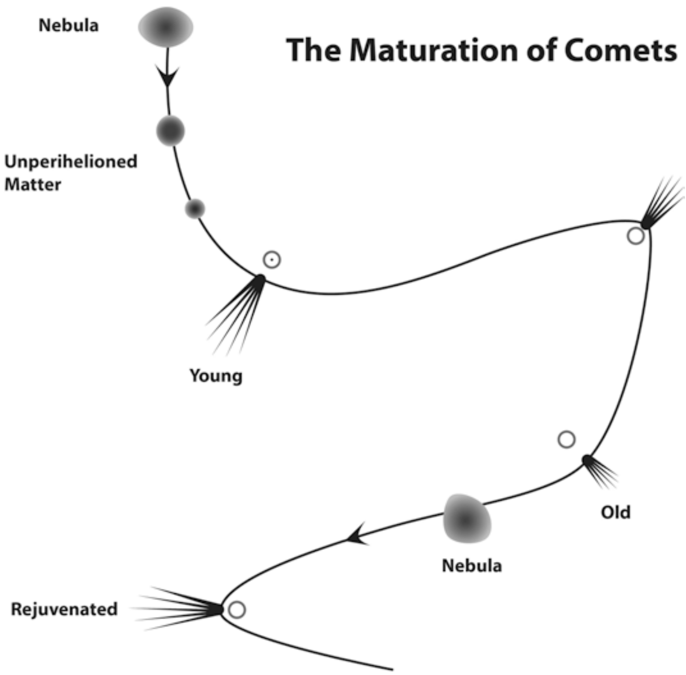


Fig. 2.8 Author's schematic drawing of Herschel's (1812a) hypothesis on the "maturation" of a comet over its lifetime. Starting at the top, the comet's planetary body and its accompanying atmosphere form in a nebula collapsing due to gravity; this atmosphere of "unperihelioned matter" has not yet passed close by a star. The body then moves between the stars, by chance passing close enough to stars to have its atmosphere "perihelioned" (heated and swept away), its trajectory changed, and its tail formed. The apparent vitality (brightness, length of tail) or relative age of the comet depends on its recent history of stellar encounters. Also, by chance the comet may pass through another nebula (as shown), pick up more material and thus be rejuvenated for its next stellar encounter (Drawing by Woodruff Sullivan)

his highly concentrated nebulae moving through space and growing dense by the action of gravity.

Decades before, he had first presented the notion of a slow process of "maturation" (today astronomers would say *evolution*, biologists *ageing* or *development*) in which a nebula under the influence of gravity eventually produced a central planetary body or a star (Fig. 2.9). And now comets providentially allowed one to catch an object in this very act of transformation. As the planetary body and its large atmosphere approached the Sun and its intense rays, the atmosphere gave off vaporous material (plus possibly unspecified "elastic volatile substances" and "subtile fluids"), leading to a much smaller atmosphere – Herschel called a comet's passage through its perihelion "an act of consolidation."[30] The stripped comet then swung

[30] Herschel (1795:60–1) had earlier suggested that comets might well collide with our sun and thus restore its ever-decreasing mass due to emission of light particles. But in the present 1812 paper he did not mention this idea, nor specify the final resting place of the comet's stripped atmospheric material.

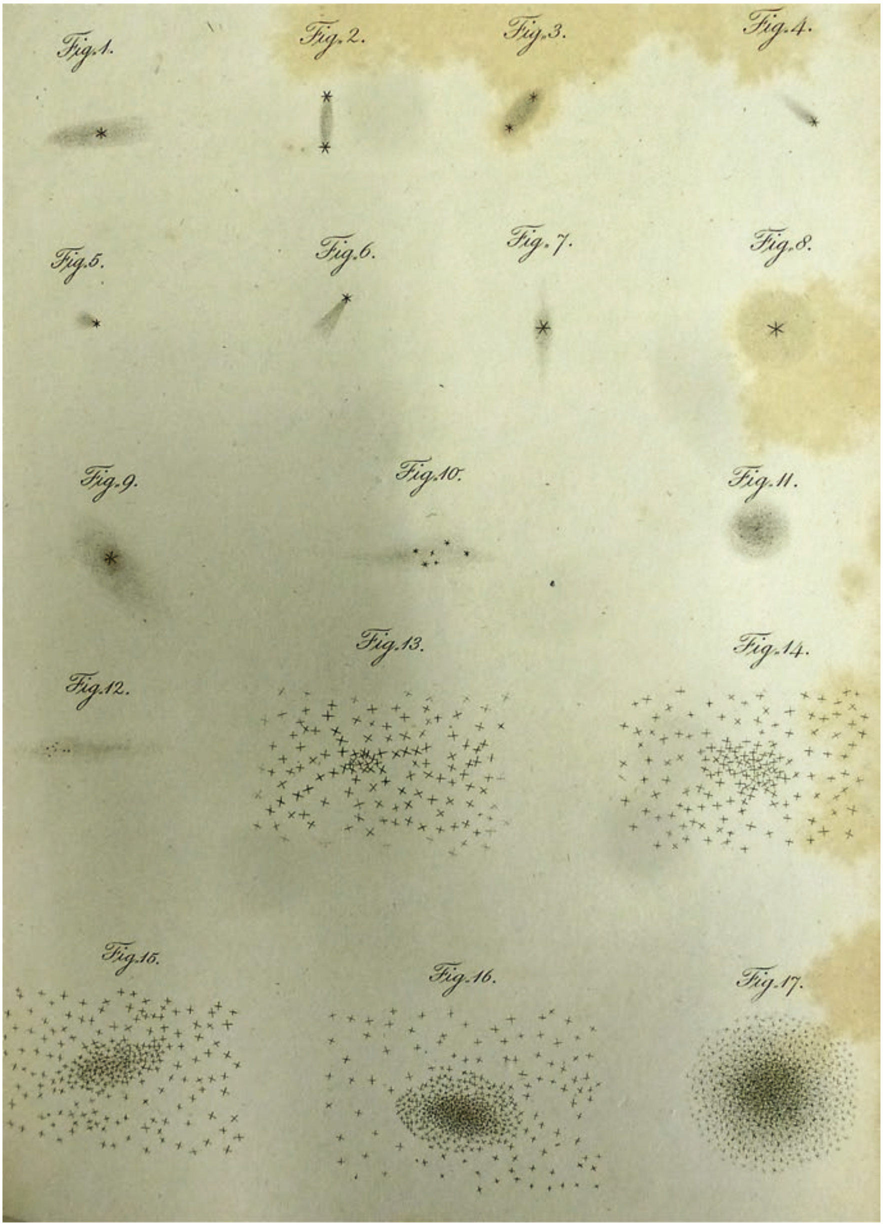


Fig. 2.9 Herschel's scheme of maturation of nebulae and stellar clusters. In the illustrated sequence nebulosity contracts due to gravity and eventually forms clusters of stars. His Figs. 1 through 12 show varying amounts of nebulosity; later stages show only stars, ending with a "globular cluster" (his Fig. 17). Herschel (1814)

around the Sun and back out into the stellar and nebular world. Eventually, it would inevitably encounter either a nebula or a star.[31] If the former, it would be rejuvenated by picking up more nebulous material – Herschel delightfully called it *unperihelioned*[32] matter. If it encountered a star, it would be ablated even more.

It would also be possible that whenever more nebulous material was picked up that the central planetary body grew in size and mass along with its atmosphere. Thus the scheme neatly incorporated an idea of planet formation and subsequent "growing up to maturity," although there was no mention of how a comet's parabolic orbit could be transformed into the circular orbit of a planet. As shown earlier in Fig. 2.8, we can imagine the various stages of a planetary body's life: birth in a condensed nebula, careening through space, swinging by one star after another in the form of a rapidly changing comet, passing through "immense regions" with "extensive strata of nebulosity," and picking up unperihelioned matter. The denizens[33] of each planetary system on its circuit would suddenly and briefly see a comet of a form and brightness dependent on its recent history and how close it passed by the star.

When yet another comet (Pons) appeared even before the Great Comet of 1811 had faded away, Herschel (1812b) dutifully studied it for 3 weeks (Table 2.1) and developed these ideas further. He was struck by the profound differences between the structures of the two comets. The central planetary body of Comet Pons was much larger at ~2600 miles (4200 km) across, but there was no comet head and only the faintest of tails. Furthermore, the brightness of the planetary body was much less than for the Great Comet; for example, it could not bear 600× magnification. Altogether, it seemed that this faintness and the great size were pointing to an object that actually *was* a planet visible because of *reflected* sunlight. This then was a very consolidated comet, lacking atmosphere to be lit up by the Sun.

Herschel arranged the three recent comets in order of consolidation. Comet Pons was in an advanced state of consolidation, having lost whatever atmosphere it originally had and having not picked up a fresh supply of unperihelioned (nebular) material. The Great Comet of 1811 had a large atmosphere of nebulous material and therefore was bright and complex (full of "beautiful phenomena") and had a small planetary body. It must have either just come from being formed in a condensed nebula, or just passed through a nebula and picked up unperihelioned (nebular) material. Lastly, the Great Comet of 1807 was somewhere in between. He clearly liked this scheme, although with reservation: "[It] appears to me most likely to throw some light upon a subject which still remains involved in great obscurity" (Herschel 1812b:234).

---

[31] Herschel never provided estimates of how long it would take before an encounter occurred (but certainly he was thinking of a *very* long time), or what the odds were that such an encounter would even take place.

[32] The term *unperihelioned* does not appear in the *Oxford English Dictionary*, but many other Herschelian neologisms do: *planetary nebula, globular cluster, asteroid, binary system, star gauge, penetration* (power of a telescope), *invisible ray* (infrared radiation).

[33] Herschel believed that all planets, moons and stars were inhabited. However, the evidence for whether or not he extended the presence of intelligent life to comets (as did many) is ambiguous.

Aspects of Herschel's Style of Science, as Illustrated by Comets

Herschel had always argued that speculating about the meaning of observations was necessary for science to make any progress. We have seen many examples of this as he interpreted the Great Comets of 1807 and 1811, and the role of comets in general. Exactly how to mix observations with rational analysis and imaginative leaps, however, required wisdom. As he stated a quarter century before these comets appeared in the sky:

> *If we would hope to make any progress in an investigation of this delicate nature, we ought to avoid two opposite extremes, of which I can hardly say which is the most dangerous. If we indulge a fanciful imagination and build worlds of our own, we must not wonder at our going wide from the path of truth and nature; but these will vanish like the Cartesian vortices, that soon gave way when better theories were offered. On the other hand, if we add observation to observation, without attempting to draw not only certain conclusions, but also conjectural views from them, we offend against the very end for which only observations ought to be made. I will endeavor to keep a proper medium; but if I should deviate from that, I could wish not to fall into the latter error.* (Herschel: 1785:213–4)

In the same vein Herschel's son John later recalled:

> *I remember it was a saying often in my Father's mouth 'Hypotheses fingo' in reference to Newton's 'Hypotheses non fingo' ['I frame no hypotheses'] and certainly it is this facility of framing hypotheses if accompanied with an equal facility of abandoning them which is the happiest structure of mind for theoretical speculation.*[34]

But what if the observations gleaned from long nights at the telescope were themselves dubious? Especially late in his career, when Herschel's standing among his contemporaries was so high and the superiority of his telescopes deemed so unimpeachable, it seems that he could publish just about any claim without serious objection. Notably, Herschel (1798) announced that the number of moons of the Georgium Sidus (Uranus) was not just the two he had found in 1787 but six. In a second case, he presented observations that Saturn's shape was not a compressed-at-the-poles spheroid, as he (and others) had earlier measured, but a significantly different squarish shape (Herschel 1805). These and other published claims turned out to be badly in error, often taking decades for others to sort out in the face of Herschel's authority.

In the case of the Great Comets of 1807 and 1811, he likewise made observational claims that, even taking his own words at face value, seemed on shaky ground. Despite this, based on these claims, Herschel built the sweeping picture of cosmic evolution described in the previous section. As an example, I will analyze one case in more detail, namely Herschel's argument that the central "planetary body" of a comet is round in shape. Showing this was very important for his entire logical edi-

[34] John Herschel:William Whewell, 20 Aug 1837, Royal Society HS 21.228. Cited by M. Bolt on p. 289 of John Herschel entry in *New Dictionary of Scientific Biography* (Vol. 3, 2007), ed. Noretta Koertge (New York: Charles Scribner's Sons).

fice of what a comet's parts were, and how and why they changed over time. Recall that he defined his key task as establishing which of two possibilities could be empirically established: (1) the bright central object *does* exhibit phases like our Moon, depending on the ever-changing geometry of the Earth-to-comet-to-Sun phase angle, or (2) it does not. If (1) were correct, the object shone because of reflecting incident sunlight, as does a planet. If (2) were correct, it had no phases and therefore was intrinsically shining, or "self-luminous."

If we read Herschel's papers carefully and dig into his archives at the Royal Astronomical Society, what do we find about how he proceeded to choose one of these options? As discussed earlier, he considered his most reliable data to come from the bright comets of 1807 and 1811, for each of which he wrote a long paper (Herschel 1808, 1812a). In October 1807 here are quotations from his observing logbook[35] (underlining mine) for the first comet[36]:

> *4 Oct. 7 feet [telescope] – [magnifying] Power 155.* [The nucleus] *is perfectly round. [p. 17]*
>
> *5 Oct.* [during daytime tests]: …<u>*contrary to my expectation*</u> [the comet nucleus] *was apparently round. [p. 18]*
>
> *18 Oct. 10 feet. The Nucleus is evidently round,* <u>*which if it were seen by light reflected from the sun, it would not be; this seems to prove that it shines by light of its own*</u>*. [p. 19]*
>
> *19 Oct.* [My new 10 feet mirror] *is uncommonly distinct and gives the diameter of small objects smaller than my former….The Nucleus is perfectly round and well defined….The night is uncommonly beautiful and the moon is not yet risen to take off from the brightness of the Comet. [p. 19]*

And from his published paper, appealing to his daytime experiments:

> *The same telescope, which could shew the spherical form of balls, which subtended only a few tenths of a second in diameter, would surely not have represented a cometary disk as circular, if it had been as deficient as are…the calculated appearances.* (Herschel 1808:157)

We here make three points: (1) Herschel is quite convinced that he could have detected a non-roundedness here. (2) He must also have known from long experience that looking at an object ~60 horizontal meters away yielded images much crisper and steadier than when looking upwards through the entire Earth's atmosphere above. (3) It is remarkable that Herschel intermixes in his *observational* log interpretations of what he is seeing – see the underlined phrases. Apparently he had

---

[35] To be more exact, William's logs are a "fair copy" (a neat copy, edited to varying degrees) made by Caroline of either William's original written notes or Caroline's notes as dictated to her by William with his eye to the telescope. Sometimes they are a Caroline copy of a copy of the originals. These copies even include reproductions by Caroline of William's sketches of star patterns, planetary features, sunspots, comets, etc. Once copied, the originals were sometimes unfortunately discarded, but the evidence of the archives is that Caroline was fastidious in her copying and made very few mistakes. It is much the same story for almost all of William's manuscripts submitted for publication – few drafts of any kind survive.

[36] These log book quotations for both comets are from RAS W.3/1.12, at cited page number.

earlier been criticized for this, for he defiantly argued that in fact when the object was in view was precisely the time to be thinking about how to understand it:

I must take notice of what will perhaps be censured in many of the observations; they may be said to be accompanied with surmises, suppositions, or hypotheses which should have been kept separate. In defense of this seeming impropriety, I must say, that the observations are of such a nature, that I found it impossible, at the very time of seeing the new objects that presented themselves to my view, to refrain from ideas that would obtrude themselves. It may even be said, that since observations are made with no other view than to draw such conclusions from them as may instruct us in the nature of the things we see, there cannot be a more proper time for entertaining surmises than when the object itself is in view.

Now, since the suggestions that have been inserted were always such as arose at the moment of the observations, they are so blended with them, that they would lose much of their value as arguments, if they were given separately. (Herschel 1801:269)

For the even brighter and larger (and therefore easier to study) Great Comet of 1811, again we quote from his logbook [underlining mine]:

18 Sep. Small 10 feet reflector. I examined the head of the comet with this instrument, as I know its distinctness to be so perfect that it will not admit of a possibility of deception. [p. 30]

16 Oct. With a very excellent, new 10 feet mirror, power 120, I see the planetary disk in great perfection, and very steadily. It is in appearance a little larger than when I saw it last night, which however I ascribe to the goodness of the mirror. The planetary disk is of a pale ruddy colour, but it is so small that its round figure can hardly be perceived. [p. 33]

17 Oct. With the new 10 feet mirror...power 120 shows the bright point extremely like the smallest [faintest] imaginable stars. The point is not otherwise than round, but the roundness cannot with certainty be perceived or ascertained with this power. [p. 34]

18 Oct. [Regarding daytime experiments with wax globules placed at 2434.5 inches [~60 meters] from the same new 10 feet mirror and with the same magnifying power as used to observe the lucid point in the comet]:

there was this evident difference that I could not a moment doubt of the roundness and well defined outline of the globule whereas the bright cometic point could not easily or at least but very doubtfully be ascertained to be round, and certainly no defined outline could be perceived. [p. 35]

These 1811 comet results are considerably more mixed than in 1807, even though his telescope was “so perfect that it will not admit of a possibility of deception.” What then does Herschel (1812a:119) publish as his conclusion, and with what degree of confidence? (underlining mine):

The smallness of the disk, even when most magnified, rendered any determination of its shape precarious; however had it been otherwise than round, it might probably have been perceived; the phasis [phase] of its illumination at the time of observation being to a full disk as 1,6 [1.6] to 2.

In the fair copy of the paper, however, the underlined passage is a replacement for a heavily crossed-out original phrase (Fig. 2.10), which with some effort can reliably be made out to be “I think it must have been visible.”[37] It appears that Herschel decided at the very end to be less certain than before, and yet he was still

[37] RAS W.3/37.1/p4.

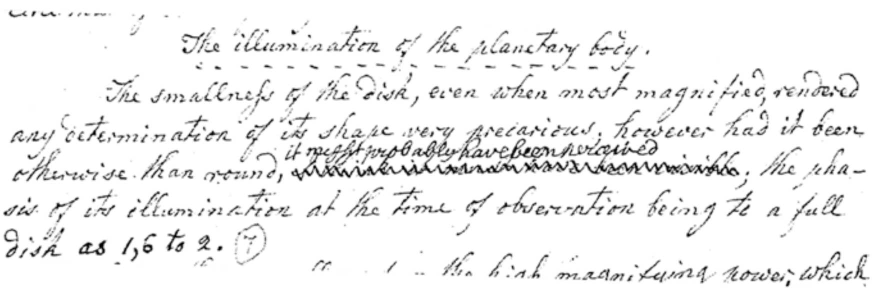

The illumination of the planetary body.
The smallness of the disk, even when most magnified, rendered any determination of its shape very precarious, however had it been otherwise than round, it might probably have been perceived, the phasis of its illumination at the time of observation being to a full disk as 1,6 to 2. (?)
the high magnifying power; which

Fig. 2.10 Revision by William Herschel to the manuscript (in Caroline Herschel's hand) submitted to the Royal Society; this text was finally published as Herschel (1812a:119). The revised text says "it might probably have been perceived"; the original crossed-out text said "I think it must have been visible." (RAS W.3/37.1/p4)

unwilling to say that, even with his best telescopes, he could not distinguish between the two cases: round or not.

What does a modern analysis indicate as to Herschel's ability to establish "roundedness"? In the Comet of 1807 paper Herschel (1807) supplied a drawing illustrating his calculated phases for the comet. These corresponded to a "gibbous comet" with about 77% of its circular disk lit, crudely equivalent to an oblong with relative dimensions of about 1.29 to 1 for its two axes. The geometry for the 1811 comet was even less favorable, with the predicted lit portion now 83% of the disk, which meant one was trying to distinguish between (1) a phase effect, indicated by slightly non-equal axes of ratio 1.25 to 1, each ~0.8″ in size and perhaps accompanied by a very small darkish region, and (2) no phase effect, indicated by equal axes. In his published article Herschel stated the 1.25 ratio (quotation above), but thought it unwise to show, as he had for the 1807 comet, an illustration of the predicted phase shape. Figure 2.11 shows what such a diagram might have looked like.[38] It would have been extremely difficult to visually establish with any certainty the "non-roundedness" or roundedness of the nucleus. Conspiring against one was its very small angular size, poor contrast with the surrounding comet head, and distortions from atmospheric scintillation causing rapid changes in intensity and position.[39]

In conclusion, Herschel often pushed himself to the very limits of what his instruments and his eye could reliably deliver. He made serious efforts to understand exactly where those limits were and how to handle them, but in the end often succumbed to his predilection to put forth what he himself called "conjectural views" for which the evidence was less than solid. These conjectures, as here, were almost always in the direction of shaping and/or backing his general principles of how the universe worked.

---

[38] Using Voyager planetarium software, I have verified Herschel's calculated phases and distances for these two comets.

[39] Today we know that each comet indeed does have a solid, icy body at its center, but its size is only ~10 km, meaning that Herschel had no chance of discerning it; only spacecraft passing close by comets have been able to see such nuclei. We do not know what apparent feature Herschel observed and measured.

Fig. 2.11 How the central planetary body of the Great Comet of 1811 might have appeared to Herschel. The phase is for a disk 83% lit, such as Herschel was attempting to discern. The planetary body was of order 1″ in diameter, surrounded by the bright comet's head of diameter ~240″ (only the very central part of the head is shown) (Drawing by Woodruff Sullivan)

Herschel's Cometary Concepts in Context

Herschel's concepts regarding comets were hardly wholly novel, although we find in his papers not a single citation of earlier authors.[40] We will start this brief review of earlier work with Newton, whose mathematical work on the nature of orbits heavily relied on comet observations.[41] He took comets to be hot, extremely dense, solid bodies with the mass of a planet and considered them to function "for the perpetual interchange of all things." This included colliding with the Sun (or stars) so as to replenish their brightness and sometimes cause great outbursts.

Subsequent Newtonians took this interchange to include both the bringing of life, or at least its raw materials (especially water and other vital, subtle "spirits"), as well as the destruction of Earth's life and perhaps even the entire planet (as proposed, for example, by Halley and later Pierre Louis Moreau de Maupertuis). Comets were blamed for the Deluge and predicted to cause the future Apocalypse. In 1749 the Comte de Buffon wrote in his magisterial *Histoire Naturelle* that comets had led to the formation of planets by drawing from the Sun filamentary material that eventually coagulated into planets. One popular author on whom Herschel cut his teeth while still a musician in Bath was James Ferguson. His *Astronomy Explained upon Sir Isaac Newton's Principles* was a standard text of the day (Herschel probably read the 4th edition of 1773). Ferguson faithfully followed

[40] Although during Herschel's era citations were far less frequent than today, my impression is that Herschel, even for his time, was below average in citing other's work.

[41] In this brief review I rely largely on Schaffer (1980), who was the first to analyze Herschel's ideas on comets vis-à-vis his cosmology, as well as Schechner Genuth (1997) and Heidarzadeh (2008).

Newtonian ideas, but went further by saying that comets and planets are probably all inhabited, not at all an unusual idea for the day (Crowe 1986).

Two of Herschel's contemporaries, astronomer/mathematicians Jérôme Lalande (a frequent correspondent with the Herschels and once a visitor) in France and Johann Lambert in Germany, prominently developed cometary cosmologies (Schaffer 1987). They saw comets as guarantors of Solar System stability as well as threats to the welfare of humans, and as signs of God's providence as well as a means to understand the geological history of Earth. In particular, Lambert (1761) argued for a non-changing Solar System in which comet-planet collisions did not happen despite his argument that several million comets resided in the known Solar System. These comets were not only inhabited by intelligent beings but moved from one star system to the next. In contrast, Lalande emphasized that comets could well collide with planets, that the Solar System and its orbits were continually changing, and that only a few hundred comets existed at this time.

By 1800 the field of cometography had no consensus on the basic properties of comets except for their orbits. After 40 years of study, in 1803 Lalande still considered the puzzles of comets the most important to solve in astronomy: "I dream of nothing but comets; I talk of nothing but comets; I recommend nothing to my correspondents but searching for comets, when I write to them that the only thing which astronomy lacks is the understanding of comets."[42]

Which of these predecessors influenced Herschel? If we examine the scheme described in his 1812 paper, we find that virtually all of its individual features had been proposed by others well before:

- Comets falling into the Sun to reverse its wasting away went back to Newton.
- A solid body sitting at the core of a comet was assumed by many, although no one before Herschel had claimed to see it, let alone measure its diameter.
- Observing phases of the central body was an old idea and one uncertain claim had even been made in 1744 (reported much later by Laplace).[43] Herschel was certainly the only person who authoritatively reported detecting such phases.
- Comets traveling between star systems was also not a new idea. It was part of Lambert's (1761) cosmology.[44] We don't know if Herschel first learned of this in Lambert's original book (in German), but we do know that he read an English translation of 1800 (even before it was published) because he left ten pages of detailed notes for us, criticizing it in the strongest language ("What an abuse of words is this kind of language"; "The author seems to be perfectly in the secrets of the Creator") (Hoskin 1978; Crowe 1986:68).[45] But although Herschel rejects most of Lambert's ideas, he did adopt one: namely that comets move from star to

[42] *Bibliographie Astronomique* (Paris), 850 (1803); cited by Schaffer (1987:67).

[43] Schechner Genuth (1997:209).

[44] The idea also shows up in the philosopher David Hume's work *Dialogues concerning Natural Religion* (1779); cited by Schechner Genuth (1997:213–4). As an aspiring 22-year-old musician, Herschel had dinner with Hume in Edinburgh in 1761.

[45] RAS W.7/2.1.

star. He would have also seen this suggestion in 1788 in a short publication by Henry Englefield that was designed to assist observers searching for the predicted return of the comet of 1661:

I cannot help therefore suspecting [*that some comets exist*] *whose orbits may have been so far altered, as totally to quit the sun, and wander through the immeasurable voids of space, till they fall within the sphere of attraction of some other star (an hypothesis by no means improbable).*[46]

Comets transmuting into planets thus was not at all a new notion, but what *was* new with Herschel was the scheme of connecting his nebulae to comets, and laying out a transformational process in which a nebula spawned a small planetary body that wandered through space and happened upon stars, each time becoming a transient comet. Another feature of the scheme was the spent comet possibly growing in mass by passing through more nebulae, being rejuvenated as a comet, and eventually (no details given) becoming a proper planet.

Finally, Herschel's research is intimately tied to his French contemporary, Pierre-Simon Marquis de Laplace, giant of celestial mechanics. Herschel had extensive discussions with Laplace while visiting Paris in 1802. Over the period 1796–1824 Laplace published five editions of his authoritative *Exposition du Système du Monde*, designed to explain the cosmos without a single equation. Herschel's work on comets was not mentioned in *Exposition* until the fourth edition in 1813 (the first after Herschel's publication in 1812 of his scheme), when Laplace mentioned with approval the idea of comets forming by the condensation of distant nebulae, traveling between stars, and losing material whenever closely encountering a star (Schechner Genuth 1997:208–12; Heidarzadeh 2008:196–9).[47] For Laplace these alien comets removed a serious problem he had had explaining the peculiar orbits of comets as part of what came to be called his "nebula hypothesis" for the origin of the Solar System. This hypothesis dominated thinking throughout the nineteenth century. Laplace's proposal was similar to Herschel's gravitational mechanism for making a star and planets from collapsing nebular material, but Laplace supplied more details concerning conservation of angular momentum, planets forming from rings of material, etc.

Herschel's Universe

Although this paper has described only William Herschel's observations and ideas on comets, his cometary work nicely leads us into his broader thinking. He did not segregate his research on our Solar System (Sun, planets, moons and comets) from

[46] Englefield, H. (1788). p. 9 in *Tables of the Apparent Places of the Comet of 1661, Whose Return is Expected in 1789*. London: P. Elmsly. Also see footnote 3.

[47] Laplace also argued that the mass of at least one comet was less than 1/5000 the Earth's mass, based on the fact that he could find no perturbations on the Earth's orbit (specifically the length of the year) arising from the close passage (0.015 AU) of the comet of 1770 (Heidarzadeh 2008:196–9). This of course made it unlikely that comets could turn into planets.

that on the sidereal universe beyond (nebulae of many kinds, binary stars, variable stars, star clusters) – they were all parts of the same novel cosmology. Simon Schaffer (1987:62) has called Herschel "the most radical cosmologist of the period."

Throughout his astronomical career one finds him guided by basic principles when trying to make sense of the phenomena he observed with his unmatched telescopes. His voluminous observations, of every possible target, including many types never before seen, were interpreted within an epistemological framework consistent with:

1. A *teleological, ordered and knowable universe* designed by a Creator such that everything in it had its purpose, and nothing was ever "useless."
2. A *unified universe* wherein all the parts fit together beautifully.
3. An *inhabited universe* fit throughout for intelligent creatures.

These principles, when combined with his decades of observation, led him to:

4. An *active, changing universe* in which all objects were continually forming, maturing, and dying.
5. A *universe vastly extended in time and space.*

In this paper we unfortunately do not have enough of Herschelian time and space to discuss these cosmological principles in any detail. But we have already seen many signs of Herschel's universe solely through the lens of his comet research (which comprises only 8 of his 73 lifetime articles in *Phil. Trans.*).

With regard to a purposeful universe made by a Creator, Herschel refers to comets as "tools, probably designed for some salutary purposes" in nature's "great laboratory," and required to save the Sun from wasting away as it continually loses particles of light:

> *Many of the operations of nature are carried out in her great laboratory, which we cannot comprehend; but now and then we see some of the tools with which she is at work....This throws a mystery over [the comets'] destination, which seems to place them in the allegorical view of tools, probably designed for some salutary purposes to be wrought by them; and, whether the restoration of what is lost to the sun by the emission of light...may not be one of these purposes, I shall not presume to determine….*
>
> [considering comet orbits in general] *it appears clearly that they may be directed to carry their salutary influence to any part of the heavens.* (Herschel 1795:60–1)

Regarding a cosmical unity and an ordered universe, recall his words in the letter of 1781 cited earlier:

> *….uniting* [the Cometary and Planetary System] *together by that admirable connection already discovered in so many other parts of the creation….the wonderful order that reigns throughout the whole Solar and Sidereal System.*[48]

To Herschel the concept of *planets* was central. A planet was a solid body with an atmosphere that fostered habitation by intelligent beings adapted to its conditions. The usual planets and moons (and later, asteroids) were of course included,

[48] Herschel:J. Banks, 19 Nov 1781, RAS W.1/7.

but also potentially comets (with their central "planetary body," perhaps still forming) and even stars, including the Sun. The Sun was evidently the grandest planet of our Solar System:

> *The sun, viewed in this light, appears to be nothing else than a very eminent, large, and lucid planet….Its similarity to the other globes of the Solar System with regard to its solidity, its atmosphere, and its diversified surface; the rotation upon its axis, and the fall of heavy bodies, leads us on to suppose that it is most probably also inhabited, like the rest of the planets, by beings whose organs are adapted to the peculiar circumstances of that vast globe.* (Herschel 1795:63)

> [My ideas on the sun given in 1795] *may be legitimately applied to the stars; whence it follows that stars, although surrounded by a luminous atmosphere, may be looked upon as so many opaque, habitable, planetary globes; differing, from what we know of our own planets, only in their size, and by their intrinsically luminous appearance.* (Herschel 1814:263)

He emphasized that this was not some wild speculation (as others had done in the past), but rather an eminently scientific conclusion, based on detailed observations and plausible deductions.[49] By analogy he further pointed out that:

> *We may have an idea of numberless globes that serve for the habitation of living creatures. But if these suns themselves are primary planets, we may see some thousands of them with our own eyes; and millions by the help of telescopes.* (Herschel 1795:68)

All stars thus have a teleological purpose, even if no planets of the usual kind can orbit them (say, in a crowded star cluster): "Many stars, unless we would make them mere useless brilliant points, may themselves be lucid planets." (Herschel 1795:71).

Herschel's unified and inhabited universe was also constantly undergoing change, and here Herschel appealed to processes of maturation (ageing) threading throughout space and time. We have seen his notion of comets, perhaps the most spectacular of all changeable phenomena in the firmament, as just one manifestation of a cyclic pathway that encompassed interstellar nebulae, stars and planets (Fig. 2.8). But based on his thousands of nebulae and star clusters, categorized into dozens of forms, Herschel also developed a second pathway for maturation. Gravity was the driving force for nebulosity to collapse and eventually turn into a star or star cluster, along the way taking on more and more concentrated forms (Fig. 2.9). For both of these pathways, change happened imperceptibly (except during the comet phase) over incalculable eons. Herschel was thus in accord with his contemporary, the Scottish geologist James Hutton, whom he read and visited. Hutton studied Earth's strata and extremely slow geological processes such as sedimentation and erosion, famously concluding in his *Theory of the Earth* (1788): "We find no vestige of a beginning – no prospect of an end."

[49] See Crowe (2011) for a full historical account of the notion of an inhabited sun, an idea that started long before Herschel and, abetted by his authority and arguments, lasted well past his time. Crowe (1986) exhaustively covers the larger question of extraterrestrial life during the eighteenth and nineteenth centuries. Sullivan (2013) examines aspects of Herschel's views on extraterrestrial life, in particular his use of analogy.

Herschel's universe likewise extended not only indefinitely in time both backwards and forwards, but seemingly also in boundless space, for he calculated the faintest star clusters visible with his 40-ft (12.2 m) reflector to be at the astounding distance of 2 million light-years (taking Sirius to be at ~5 light-years), yet felt confident from his experience that still fainter, and presumably farther, stars would be revealed by a larger mirror (Herschel 1800:83–4).

William Herschel's 21 comets observed over the period 1781–1819 thus surprisingly provide a gateway into many aspects of his life and science: his collaboration with Caroline, his style of observing, his rhetoric in argumentation, his elaborate scheme for the structure and lifetime history of a comet, and much of his overall cosmology.

Acknowledgments I give many thanks first to Michael Hoskin for his friendship and the insights and facts provided by his publications on the Herschels over the past half-century. In particular, his creation of purchasable DVD's containing the entire Herschel archives of the Royal Astronomical Society has been of immense use to me and many others. Michael Crowe has also been extremely helpful in my Herschel researches. For assistance with aspects of this paper I thank Peter Abrahams, Don Brownlee, and Don Yeomans. The excellent service of the Interlibrary Loan section of the University of Washington Libraries has been indispensable, as have many librarians and archivists, in particular at the Harry Ransom Center of the University of Texas, and the Royal Society in London.

References

Bullard, M. 1988. My small Newtonian sweeper – Where is it now? *Notes & Records Royal Society London* 42: 139–148.

Crowe, M.J. 1986. *The extraterrestrial life debate 1750–1900*. New York: Cambridge University Press.

———. 2011. The surprising history of claims for life on the sun. *Journal of Astronomical History and Heritage* 14: 169–179.

Cunningham, C.J. 2016a. *Early investigations of Ceres and the discovery of Pallas*. New York: Springer.

———. 2016b. *Discovery of the first asteroid, Ceres*. New York: Springer.

Deluc, J.-A. 1809. "A letter on comets" [dated 1799]. *Nicholson's Journal of Natural Philosophy, Chemistry, and the Arts* 23: 206–213.

Dreyer, J.L.E. (Ed.) (1912; 2003 reprint). *The scientific papers of Sir William Herschel* (Vol. 1). 1912 (2003 reprint). Thoemmes Press: Bristol.

Ferguson, J. (1773). *Astronomy explained upon Sir Isaac Newton's principles*. 4th ed. London.

Heidarzadeh, T. 2008. *A history of physical theories of comets, from Aristotle to Whipple*. New York: Springer.

Herschel, C. 1787. An account of a new comet. Philosophical Transactions 77: 1–3.

Herschel, C. 1794. An account of the discovery of a comet. *Philosophical Transactions* 84: 1.

Herschel, C., and W. Herschel. 1796. Account of the discovery of a new comet. By Miss Caroline Herschel. *Philosophical Transactions* 86: 131–134. Two parts: pp. 131–2 by CH with title as given; pp. 133–4 by WH with title "Additional observations on the comet".

Herschel, W. 1781. Account of a comet. *Philosophical Transactions* 71: 492–501.

———. 1785. On the construction of the heavens. *Philosophical Transactions* 75: 213–266.

———. 1786. Catalogue of one thousand new nebulae and clusters of stars. *Philosophical Transactions* 76: 457–499.
Herschel, W. 1787a. Remarks on the new comet. Philosophical Transactions 77: 4–5.
———. 1787b. An account of three volcanos in the moon. Philosophical Transactions 77: 229–232.
———. 1789. Observations on a comet. *Philosophical Transactions* 79: 151–153.
———. 1792. Miscellaneous observations. *Philosophical Transactions* 82: 23–27.
Herschel, W. 1795. On the nature and construction of the sun and fixed stars. *Philosophical Transactions* 85: 46–72.
———. 1798. On the discovery of four additional satellites of the Georgium Sidus. The retrograde motion of its old satellites announced; and the cause of their disappearance at certain distances from the planet explained. *Philosophical Transactions* 88: 47–79.
———. 1800. On the power of penetrating into space by telescopes; with a comparative determination of the extent of that power in natural vision, and in telescopes of various sizes and constructions; illustrated by select observations. *Philosophical Transactions* 90: 49–85.
———. 1801. Observations tending to investigate the nature of the sun, in order to find the causes or symptoms of its variable emission of light and heat; with remarks on the use that may possibly be drawn from solar observations. *Philosophical Transactions* 91: 265–318.
———. 1802a. Observations on the two lately discovered celestial bodies. *Philosophical Transactions* 92: 213–232.
———. 1802b. Catalogue of 500 new nebulae, nebulous stars, planetary nebulae, and clusters of stars; with remarks on the construction of the heavens. *Philosophical Transactions* 92: 477–528.
———. 1805. Observations on the singular figure of the planet Saturn. *Philosophical Transactions* 95: 272–280.
———. 1807. Observations on the nature of the new celestial body discovered by Dr. Olbers, and of the comet which was expected to appear last January in its return from the sun. *Philosophical Transactions* 97: 260–266.
———. 1808. Observations of a comet, made with a view to investigate its magnitude and the nature of its illumination. To which is added, an account of a new irregularity lately perceived in the apparent figure of the planet Saturn. *Philosophical Transactions* 98: 145–163.
———. 1811. Astronomical observations relating to the construction of the heavens, arranged for the purpose of a critical examination, the result of which appears to throw some new light upon the organization of the celestial bodies. *Philosophical Transactions* 101: 269–336.
———. 1812a. Observations of a comet, with remarks on the construction of its different parts. *Philosophical Transactions* 102: 115–143.
———. 1812b. Observations of a second comet, with remarks on its construction. *Philosophical Transactions* 102: 229–237.
———. 1814. Astronomical observations relating to the sidereal part of the heavens, and its connection with the nebulous part; arranged for the purpose of a critical examination. *Philosophical Transactions* 104: 248–284.
Hoskin, M. 1978. Lambert and Herschel. *Journal for the History of Astronomy* 9: 140–142.
———. 2005. Caroline Herschel as observer. *Journal for the History of Astronomy* 36: 373–406.
———. 2013. *Caroline Herschel: Priestess of the Heavens*. Sagamore Beach: Science History Publications.
———. 2014. Caroline Herschel's life of "mortifications and disappointments". *Journal for the History of Astronomy* 45: 442–466.
Hughes, D.W. 1999. Caroline Lucretia Herschel – Comet huntress. *Journal of the British Astronomical Association* 109: 78–85.
Kronk, G.W. 1999. *Cometography: A catalog of comets*. Cambridge: Cambridge University Press. 2 Volumes.
Lambert, J. 1761. *Cosmologische Briefe über die Einrichtung des Weltbaues*. Augsburg. Available in English as *Cosmological Letters on the Arrangement of the World-Edifice*, ed. and trans. S.L. Jaki (1976, New York: Science History Pubs.). Early translations: French trans. and condensation in 1770; English trans. of French in 1800; full French trans. in 1801.

Olson, R.J.M. 1985. *Fire and ice: A history of comets in art*. New York: Walker Publishing Co.
Olson, R.J.M., and J.M. Pasachoff. 1998. *Fire in the sky: comets and meteors, the decisive centuries, in British art and science*. Cambridge: Cambridge University Press.
Schaffer, S. 1980. "The great laboratories of the universe": William Herschel on matter theory and planetary life. *Journal for the History of Astronomy* 11: 81–111.
———. 1987. Authorized prophets: Comets and astronomers after 1759. In *Studies in eighteenth-century culture*, ed. J. Yolton and L.E. Brown, 17: 45–74. East Lansing: Colleagues Press.
Schechner Genuth, S. 1997. *Comets, popular culture, and the birth of modern cosmology*. Princeton: Princeton University Press.
Steinicke, W. 2010. *Observing and cataloguing nebulae and star clusters: From Herschel to Dreyer's New General Catalogue*. Cambridge: Cambridge University Press.
Sullivan, W.T. 2013. Extraterrestrial life as the great analogy, two centuries ago as well as in modern astrobiology. In *Astrobiology, history and society: Life beyond earth and the impact of discovery*, ed. D.A. Vakoch, 73–83. Heidelberg: Springer.
Yeomans, D.K. 1991. *Comets: A chronological history of observation, science, myth, and folklore*. New York: Wiley.