JHA, xxxiii (2002)

THE RISE AND FALL OF THE FIRST SOLAR CYCLE MODEL

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1. *Prolog im Himmel*

> "For now 40 days not even the smallest spot could be seen on the Sun, something I have never witnessed before. It is puzzling that at certain times the luminous matter can overflow and cover the whole surface of the Sun, while at other times there is not enough of it to do so; or are there low and high tides carrying this matter to the poles? which celestial body has such close ties to the Sun, to cause on it such monstrous upheaval?"[1]

From the beginning of telescopic observations of sunspots in the early seventeenth century, observers had been baffled at their endless variety of form, and apparently random manner of appearance and disappearance. In his 1613 *Letters on sunspots*, Galileo had taken due note of the fact that sunspots were rarely seen outside of a heliocentric latitude band about 30° wide on either side of the solar equator, but this was to remain the only *spatial* pattern associated with sunspots for two and a half centuries. By the end of the eighteenth century various authors, most notably the Danish astronomer Christian Horrebow (1718–76), were expressing the opinion that a cyclic *temporal* pattern might exist, though none had yet been identified.[2]

In a short paper published in 1843 with the anything but eye-catching title "Sonnen-Beobachtungen im Jahre 1843", the German amateur astronomer Samuel Heinrich Schwabe (1789–1875) announced that the number of sunspots visible on the face of the Sun waxed and waned on a 10-year cycle.[3] Little attention was paid at the time to Schwabe's remarkable discovery, until it was pointed out in 1852 that the period of the sunspot cycle coincides with a marked periodicity in geomagnetic activity. The sunspot cycle rapidly became a topic of great interest outside the circle of sunspots observers.

The physical nature and origin of sunspots were topics of great debate amongst nineteenth-century scientists, with ideas ranging from meteoritic impact to volcanic-like eruptions or cyclone-like atmospheric disturbances.[4] Perhaps the only point of agreement amongst the proponents of these various theories was that sunspots belong to the realm of physics, and that, as such, their spatiotemporal behaviour must be subjected to orderly physical laws. The habitually prolix Richard Christopher Carrington (1826–75) managed to articulate this *Weltanschau* succinctly in the introductory chapter of his 1863 tome on sunspots: "That the Solar phenomena, amid the universal subjection to order and law, should alone be subject to caprice could never gravely be entertained by any mind of philosophical training."[5]

In their attempt to impose order to sunspot observations, it is only natural that nineteenth-century astronomers should have sought a causal agent in the archetype of celestial clockwork: planetary motion. In the mid-nineteenth century the idea not

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only was considered seriously by most working astronomers, but also stood as the only quantitative model of the solar cycle on the books for the following half-century. Although many hypothetical explanations of the sunspot cycle were put forth during that period, only the planetary influence hypothesis reached the status of 'model', in the sense of a quantitative explanatory construct allowing numerical predictions to be made and tested. This paper tells the story of this first model of the solar cycle, and of some of the key figures who presided over its rise and fall.

2. *Gravity's Rainbow*

One person who did take due notice of Schwabe's results was the Swiss astronomer Johann Rudolf Wolf (1816–93, see Figure 1). Educated in Zürich, Vienna, and Berlin, Wolf taught mathematics and physics in Bern until his appointment as director of the local observatory in 1847. In December of that same year, his interest in sunspots was fired by the observation of a spectacularly large sunspot group. Already aware of Schwabe's discovery and well-versed in the historical astronomical literature, Wolf embarked on a program of sunspot observations that he pursued to the year of his death. Perhaps more importantly, he also began historical researches aimed at reconstructing the form of the sunspot temporal variations prior to Schwabe's time, using records of observatories across Europe. The end result of this historical detective work were time series of the yearly-averaged and monthly-averaged number of sunspots visible on the solar disk, which even today remain the datasets most intensively studied by solar cycle modellers. By 1852 he had revised Schwabe's 10-year cycle period to 11 years, and offered evidence for significant variations in the cycle's duration as well as longer, secondary periodicities superimposed on the primary cycle. In 1855 he moved back to Zürich as professor of astronomy at the Polytechnikum, and later became the first director of the observatory inaugurated there in 1864. Already in 1859 he published tentative dates for sunspot minima and maxima back to 1610, and by the early 1860s, yearly sunspot numbers back to 1750.

By his own account, Wolf began to contemplate the possibility of a causal relationship between planetary motions and the variations in sunspot numbers shortly after noting the coincidence between the observed period of sunspots numbers and geomagnetic activity in 1852. His most elaborate attempt at quantifying this idea, however, is found in Part VIII of his "Astronomische Mittheilungen".[6] Wolf began with the assumption that planetary influences on sunspot numbers are directly proportional to each planet's gravitational pull on the Sun, i.e., to m/a^2, where m and a are the planet's mass and heliocentric distance, respectively. Table 1 compiles this quantity for the nine solar system planets. Jupiter is clearly the dominant influence, with Venus, Earth and Saturn as distant, approximately *ex aequo*.

Accordingly, Wolf fitted his monthly sunspot number (R_Z) reconstruction with a mathematical expression of the form

$$R_Z(t) = A + B \times [1.68 \sin(585^\circ.26t) + 1.00 \sin(360^\circ t) + 12.53 \sin(30^\circ.35t) + 1.12 \sin(12^\circ.22t)], \tag{1}$$

FIG. 1. Johann Rudolf Wolf in the early 1890s (courtesy of the Bildarchiv ETH-Bibliothek, Zürich).

TABLE 1. Gravitational and tidal parameters for solar system planets. Planetary masses (m) are measured in units of Earth's mass, semi-major axes (a) in Astronomical Units, and e is the orbital eccentricity. The numbers listed in parentheses give the percent contribution of each planet to $\Sigma m/a^2$ and $\Sigma m/a^3$.

Planet	P [yr]	a [AU]	e	m/a^2	% sum	m/a^3	% sum
Mercury	0.24	0.39	0.206	0.394	(2.5)	1.01	(15.4)
Venus	0.62	0.72	0.007	1.560	(9.9)	2.17	(33.0)
Earth	1.00	1.00	0.017	1.000	(6.3)	1.000	(15.2)
Mars	1.88	1.52	0.093	0.0476	(0.3)	0.0313	(0.5)
Jupiter	11.86	5.20	0.048	11.7	(74.1)	2.25	(34.3)
Saturn	29.46	9.54	0.056	1.04	(6.6)	0.109	(1.6)
Uranus	84.07	19.18	0.046	0.381	(0.2)	1.98×10^{-3}	(0.0)
Neptune	164.80	30.06	0.010	0.00188	(0.1)	6.25×10^{-4}	(0.0)
Pluto	248.60	39.44	0.248	1.28×10^{-6}	(0.0)	3.26×10^{-8}	(0.0)

with t measured in years, and the zero point of the time scale set to 1836.[7] Note that this is a rather restricted fit, involving only the offset and amplitude parameters A and B, for which Wolf found best-fit values $A = 50.31$ and $B = 3.73$ for the time interval 1836–49. The resulting fit was found to hold reasonably well over the wider time interval 1834–58, and on this basis Wolf suggested, tentatively and with all due caution, that the overall shape of the curve is set by Jupiter, small variations in its peak and minimal amplitudes are due to Saturn, and irregularities on timescales less than a year to the combined effects of Venus and Earth. Note here that Wolf's approach is a global one, as he focused on the variations of the sunspot number with planetary distances, without any consideration being given to the *location* of sunspots on the solar surface, or to planetary ecliptical longitudes.

Carrington was another astronomer who was impressed and inspired by Schwabe's discovery of the sunspot cycle. The well-endowed son of a wealthy brewer, Carrington began his own sunspot observations in November 1853 and pursued them until 1861. He reaped a rich harvest, including his discovery of the equatorward migration of sunspots in the course of the cycle (1858), and of the Sun's differential rotation (1859). He also carried out the first, albeit serendipitous, well-documented observation of a solar flare (1859). His attempt to link sunspots to planetary influences is far less elaborate than Wolf's, but his professional stature as the leading British expert on sunspots gave great weight to his (rather confused) musings on the issue.

Although a careful and diligent observer, Carrington was typically reserved in advancing physical interpretations of his observations. His 1863 tome on sunspots, 248 pages long plus 166 plates, restricts physical discussion to the final two pages. In his last plate, Carrington presented a plot of Wolf's sunspot number time series, accompanied by a time series of the Sun–Jupiter radius vector. Figure 2 is a contemporary reconstruction of Carrington's plot. He wrote:

> I purposely contrast with it [Wolf's sunspot curve] the variations of Jupiter's Radius Vector, as offering the only approximate agreement which I have been able to perceive. It will be seen that from the year 1770 there is a fairly general agreement between maxima of frequency and maxima of Jupiter's Radius Vector, and between minima and minima, with such an amount of loose discrepancy as to throw grave doubt on any hasty conclusion or physical connexion.[8]

Showing admirable deference to data, Carrington went on to argue that the marked disagreement between the two curves for the earlier two cycles *cannot* be ascribed to errors in Wolf's historical reconstruction, and therefore that the agreement shown by the two curves between 1770 and 1860 is to be considered fortuitous. Nonetheless, and presumably with the meteoritic theory of sunspots in mind, he concluded his brief discussion with the statement:

> I suggest that it deserves consideration whether the mass of Jupiter may not affect the variations of Solar Spot-frequency indirectly through his possible intermediate action on the ring of matter constituting the appearance termed the Zodiacal light.[9]

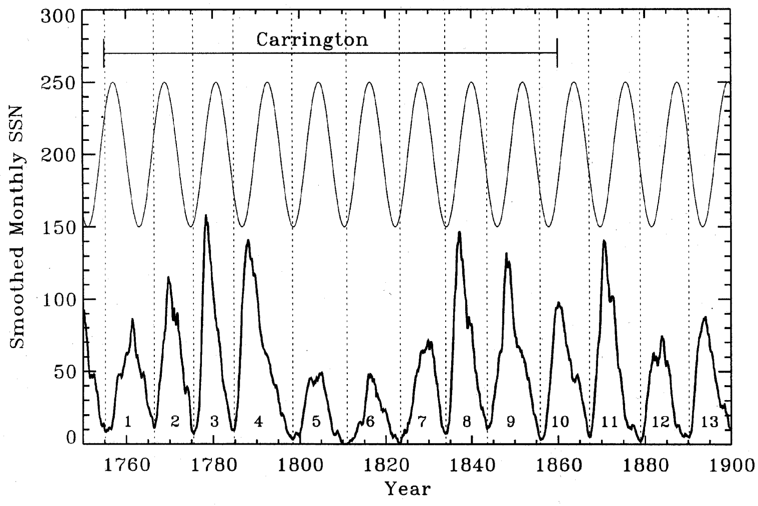

FIG. 2. The thick solid line is the (smoothed monthly) Wolf sunspot number, with the vertical dotted lines indicating the epochs of sunspot minima. Cycles are (anachronistically) numbered according to present-day usage. The range of Carrington's original 1863 diagram (Plate 166) is indicated along the upper horizontal axis. The thin sinusoidal line gives the Sun–Jupiter distance, in arbitrary units. Note how, from about 1770 to 1835, sunspot minima coincide quite well with Jupiter's closest approach. The agreement degrades rapidly outside this interval, as one would expect from two semi-periodic signals of close, but not identical period (here 11.1 yr for sunspots, and 11.86 yr for Jupiter's orbital period). Note also a hint of Wolf's 56 yr amplitude modulation of the primary cycle.

Neither Carrington's logic nor his intent is transparent here, and it is perhaps not surprising to see, in subsequent years, both opponents and proponents of the planetary influence thesis cite Carrington as an authority in support of their respective, opposite views.

3. *The Monkey Wrench Gang*

Fortunately, sunspot research in Britain had not awaited Carrington's monograph to get seriously underway. In April 1854, John Herschel (1792–1871) had written to the overseeing Committee of Kew Observatory, pressing the need for securing daily photographs of the Sun. Kew Observatory was at the time primarily engaged in the calibration and testing of assorted scientific, navigational, and meteorological instruments, and was well-established as a leading institution for magnetic measurements. The recently uncovered link between sunspots and geomagnetic activity thus made Kew a site of choice to host a sunspot monitoring program. The Kew Committee sought the technical advice of Warren De La Rue (1815–89), then a rising star in the nascent field of astronomical photography. In June of the same year, the Council of the Royal Society granted the funds necessary for the construction and operation of the required apparatus, and De La Rue was put in charge of the project.

Upon returning to England after completing his education in France, De La Rue joined his father's printing business, where he developed his unusual abilities in matters technological. His first scientific endeavours were in the field of electrochemistry, and include the invention of the silver-chloride battery. His combined interests in chemistry, astronomy, and technological innovation lead him naturally to astronomical photography, achieving wide acclaim first for his remarkable photographs of the Moon. He later obtained the first scientifically useful eclipse photographs in 1860.

The Kew photoheliograph, as the instrument commissioned by the Royal Society came to be called, secured the first useful solar photographs in March 1858, but it took another few years before De La Rue had perfected its design and operation. Meanwhile, a new director was appointed at Kew Observatory; one, moreover, who took a keen and immediate interest in the new sunspot program.

Balfour Stewart (1828–87, see Figure 3) entered St Andrews University at the early age of thirteen, finishing his studies at Edinburgh five years later. After a brief apprenticeship in a business firm and a soon aborted business venture in Australia, he returned to Edinburgh University where he worked as an assistant until his appointment as Director of Kew Observatory in 1859. From early on, Stewart developed lasting research interests in the area of terrestrial magnetism, and the possible

FIG. 3. Balfour Stewart, exact date unknown but most probably during his years as director of Kew Observatory (courtesy of Living Archives).

relations between solar phenomena, and terrestrial magnetism and meteorology. It was inevitable that after 1852 his attention be attracted to sunspots, and to the unknown mechanism governing their cyclic variations in numbers. Hailed by some as a pioneer of spectral analysis, characterized by others as "one of the most loveable of men, modest and unassuming, but full of the most weird and grotesque ideas",[10] Stewart was to step resolutely into the *terra incognita* of planetary influences on sunspots.

With De La Rue immersed in instrumental matters, Stewart was clearly the driving force behind the program of research on planetary influences on sunspots carried out at Kew. Already in 1864, he read to the Royal Society of Edinburgh a paper in which he focused on *local* planetary influences, specifically correlations between a planet's ecliptical longitude and the appearance, growth and decay of individual sunspots as a function of their heliographic longitude.[11] His approach is thus quite original and distinct from the *global*, longitudinally averaged influences implicit in Wolf's work. Using the first three-and-a-half years of solar photographs taken at Kew and at De La Rue's private observatory in Cranford, he detected a tendency of spots to appear and grow in size as solar rotation carries them away from the ecliptical longitude of Venus, and to decay and disappear when moving towards the side of the Sun facing Venus. This general approach to the problem was to become the primary working hypothesis underlying much of the subsequent work on planetary influence carried out at Kew Observatory.

By the beginning of 1862 the photoheliograph was operating to De La Rue's satisfaction, and the sunspot monitoring program began in earnest. De La Rue and Stewart had by then secured the assistance of Benjamin Loewy (d. 1892), hired to tackle the tedious task of numerical data reduction. Between 1865 and 1873, nine papers or extended abstracts were communicated to the Royal Society and the Royal Astronomical Society, all under the authorship of "De La Rue, Stewart, and Loewy"; henceforth the trio is referred to as the "Kew team".

The Kew team approached their work with remarkable care. In view of the fact that sunspots were known to be associated with depressions in the solar photosphere, they first established numerical corrections to be applied to the geometrical foreshortening observed as spots approach and recede from the solar limb. They also carried out careful comparisons of sunspot areas computed from the drawings of Schwabe and Carrington, with those calculated from their photographs, to assess the degree to which the former could be used to extend backward in time the sunspot area time-series initiated at Kew.

The year 1865 marks the Kew team's first public reports on the topic of planetary influences,[12] these first results being in line with Stewart's 1864 inferences. By 1866 they discovered a new interesting trend, namely that sunspots seem to appear closer to (farther from) the equator when Venus is closer to (farther from) the Sun's equatorial plane.[13] By 1867, using Carrington data for 1853–60, they also detected an influence from Jupiter, and felt sufficiently confident in the reality of the inferred patterns to embark on a systematic re-examination of Schwabe's sunspot drawings, as a means of independent verification. These evidently did not hold as well as expected; by 1870, using a combined Schwabe + Carrington + Kew dataset covering the 1832–68 time period, they were examining trends involving combinations of planets, finding that sunspot activity is above average when either Venus and Jupiter or Venus and Mercury are near conjunction, and below average when the same planetary pairs are near opposition.[14] This also must have failed to hold, as they were soon back working only with the Carrington-Kew joint dataset for 1854–66, and embarked on what became their final, most elaborate analysis of the problem.[15]

The data reduction procedure adopted in the Kew team's 1872 paper is quantitatively a more elaborate version of Stewart's 1864 approach. The visible disk of the Sun is divided into ten contiguous longitudinal sectors of 14° in angular width, jointly spanning 70° on either side of the solar central meridian (see Figure 4). Day after day, the areas of all sunspots present in each sector, as measured on the daily photographs, are summed. The resulting dataset is then partitioned according to four possible planetary configurations: whether a given planet is approximately in conjunction with Earth (**A** on Figure 4), in opposition (**C**), or in quadrature (**B**, **D**). The temporal length of the partitioning intervals are chosen to correspond to a quarter of the synodic period of the planet under consideration, so that the dataset is divided more or less evenly into the four possible planetary configurations.

This results in three sets (Mercury, Venus, and Jupiter) of four curves (one per planetary configuration) depicting the variations of summed sunspot area A, measured in units of millionth of the solar disk area (SDA), as a function of planetary ecliptical longitude. The Kew team displayed their numerical results in terms of the deviations (ΔA) about the mean ($\langle A\rangle$), rescaled to an "average" spot of area 1000 in the same units; i.e.,

$$\Delta A = \frac{1000}{\langle A\rangle}(A - \langle A\rangle), \qquad [10^{-6}\mathrm{SDA}]. \tag{2}$$

These are plotted on Figure 5 (dots and thin lines), with longitude zero corresponding to conjunction (position **A** on Figure 4). Note that, in view of the scaling adopted, the largest deviations in spot area are only at the 5–10% level.

The Kew team did not display their results in quite this way; they first smoothed the curves using a sequential two-step pairwise averaging, numerically identical to what would be called, in modern parlance, a 1–2–1 running mean, yielding the thick solid lines on Figure 5. More significantly, they plotted each segment on an individual diagram (see their Plate I);[17] whether intentional or not, this has the effect of visually de-emphasizing the peak and troughs in the regions where the various curves overlap (e.g., such as at longitudes ≈50°, 250°, and 310° on Figure 5 for Mercury and Venus; compare with Plate I of the Kew team's 1872 paper). The team's terse interpretation of their results certainly emphasized the opposition and conjunction configurations: "the average size of a spot would appear to attain its maximum on that side of the sun which is turned away from Venus or Mercury, and to have its minimum in the neighbourhood of Venus or Mercury."[18]

Examination of Figure 5 reveals that this interpretation is certainly not the only

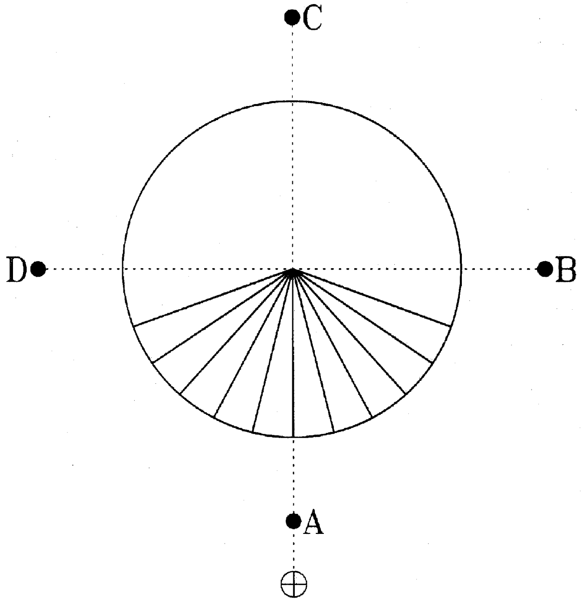

FIG. 4. The Kew Team's method for tracking variations of summed sunspot areas across the solar disk. The diagram is drawn in the solar equatorial plane, so that planetary orbits are only approximately contained in the plane of the paper. The portion of the visible solar disk facing the Earth (⊕) is subdivided into 10 longitudinal sectors of angular width 14° spanning +/–70° on either side of the central meridian. Solar rotation carries spots counterclockwise across the sectors, and the variation of the summed spot area from one sector to the next is tabulated separately for four planetary positions (solid dots) centred around conjunction (**A**), opposition (**C**), and quadrature (**B** and **D**). The planets are also moving counterclockwise on this diagram, i.e. **A** → **B** → **C** → **D**.

one that can be inferred from the numerical results, to say the least. Evidently, the tantalizing correlations with planetary positions that the Kew team had inferred from their earlier studies failed to hold as more and more data were obtained and reduced, forcing ever more complex elaborations and additions to the model. As any (reasonable) scientist who has ever struggled to force a pet model onto a set of stubbornly uncooperating data knows all too well, there comes a time when a strategic retreat to the proverbial drawing-board can no longer be postponed. The Kew team had evidently reached that point in 1872, having in fact gone full circle and returned to the original, simple pattern inferred by Balfour Stewart in 1864.

The somewhat anticlimactic results reported in their 1872 paper are the Kew team's last published statements on the topic of planetary influence on sunspots. Changes of many kinds were taking place at Kew. In 1870 the decision was taken to hand oversight of Kew Observatory to the Royal Society, a process eventually completed in August 1871. Rapidly growing tensions with the Royal Society regarding research priorities at Kew forced Stewart to resign his directorship, and accept instead a

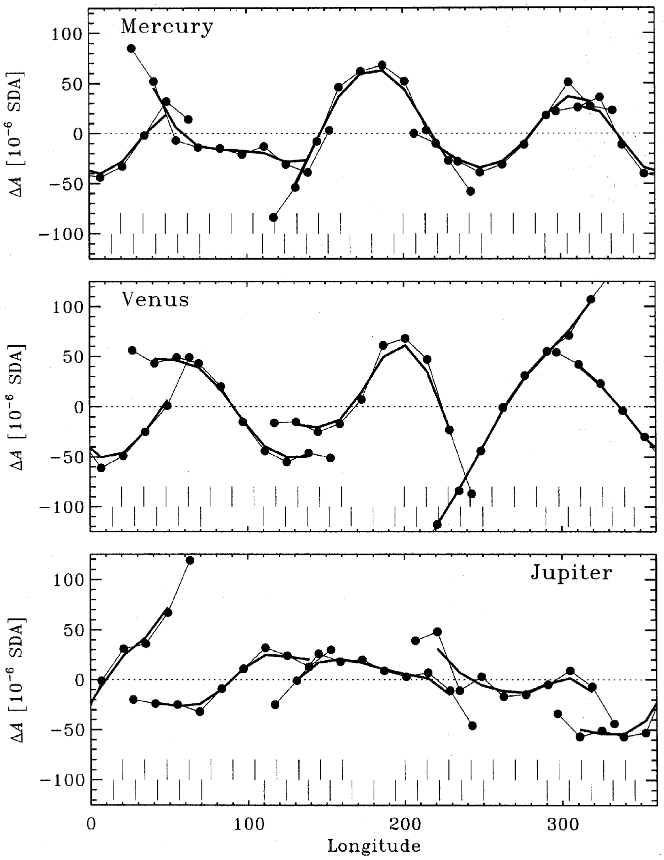

FIG. 5. Variations of the summed sunspots areas with ecliptical longitude, as calculated by the Kew team. The data are taken directly from Tables II, III and IV of their 1872 paper.[16] What is plotted (dots and thin lines) is the deviation ΔA about the mean spot area, itself rescaled to 1000 millionths of the solar disk; the peak amplitude variations are thus only at the 10% level. The thick lines are 1–2–1 running means, and the thin vertical line segments plotted along the lower horizontal axis correspond to the (overlapping) sets of sector boundaries, as viewed from the four planetary positions (**A**–**D**) on Fig. 4. Opposition (**C**) corresponds to longitude 180°, conjunction **A** to longitude 0/360°.

faculty position recently offered to him at Owens College, in Manchester. Also in 1870, Stewart was caught in a railway accident, causing him serious injuries from which he never fully recovered. Funding for the original 10-year solar photographic program came to an end in December 1871, and further work was carried out at De La Rue's personal expense. The Kew heliograph eventually ceased operation in March 1872, and in February 1873 was transferred to the Royal Observatory in Greenwich, where the solar photographic monitoring program was pursued under the direction of the Astronomer Royal.

In addition, the Kew program of sunspot studies was thrown into disarray in 1873 by a devastating event of a wholly different nature. Arthur Schuster, writing four decades later and deploring the fall into oblivion of the Kew team's investigations, adds: "This may be due to the fact, which it would be wrong now to conceal, that Mr. Loewy, to whom, in a later series of investigations, and probably in this, the numerical work was entrusted, subsequently admitted that he had not dealt candidly with the figures."[19]

Loewy's numerical misbehaviour was uncovered by Stewart, then in Manchester, in the course of looking over the printer's proofs of a paper nearing publication in the *Proceedings of the Royal Society*.[20] This forced the withdrawal, *in extremis*, of the paper, and the laborious re-analysis of the full sunspot dataset, starting all the way back with the 1862 solar photographs, a task that ended up being carried out by a newly hired assistant and privately funded by De La Rue. The revision was eventually completed and the resulting sunspot areas and solar rotational element data duly published. However, neither De La Rue nor Stewart was to revisit the topic of planetary influences, at least in print, and the full version of their 1872 paper was never published.[21]

The Loewy fiasco notwithstanding, the Kew team's work found its way in most Solar Physics textbooks and monographs published in the 1870s, and was sometimes even endorsed enthusiastically.[22] Yet, most subsequent work on the topic in the remainder of the nineteenth century shifted back to Wolf's sunspot number time series as the primary focus of attention.

4. *Torques, Tides and Tactics*

The planetary influences thesis had already begun to undergo diversification in the late 1860s, as different physical mechanisms were put forth and explored. Although the Kew team never wrote so explicitly in any of their published works, their focus on the inner planets suggests that they had in mind tidal effects, which are directly proportional to the planet's mass and inversely proportional to the cube of the Sun–planet distance (or semi-major orbital axis a).

The leftmost columns of Table 1 list this quantity for the solar system planets, from which it is readily seen that distinct subsets of planets are to be reckoned with if working in the context of a model based on tidal interaction, as opposed to direct gravitational influence, such as originally contemplated by Wolf.[23] Jupiter clearly dominates in the gravitational models, while four planets have comparable influence in the tidal context.[24]

Even though the physical state of the solar atmosphere was not yet understood, nineteenth-century astronomers were not oblivious to the fact that the magnitude of gravitational perturbations and tidal amplitudes raised by the planets were in all likelihood too small to be the *direct cause* of the sunspot phenomenon. Martinus Hoek (1834–74), then professor of astronomy in Utrecht, estimated the amplitudes of the

Venusian and Jovian tides at about one centimetre, a minute figure that, moreover, was to be revised substantially downwards in the following decades. The suggestion was instead that tides or gravitational perturbations could act as a *trigger* for sunspot formation, by perturbing the presumably delicate equilibrium of the solar atmosphere.[25]

Although comparison with the sunspot periodicities is straightforward for individual planets, the possibilities increase geometrically once pairs, triads or quartets of planets are considered in terms of their oppositions, conjunctions, or quadratures. Moreover, the significant eccentricities of some planets (Jupiter, Saturn and Mercury) add yet another set of potentially relevant timescales, namely the time intervals of joint recurrences at aphelion or perihelion. To complicate matters further, these effects all play out differently in the two main classes of models, since planets in opposition produce additive tides, even though their direct gravitational pulls are in opposite directions. Taking proper account of all this yields a computationally demanding problem; it would not be particularly useful to review the literature that arose from these attempts in the last decades of the nineteenth century. It suffices to say that the vast majority of papers published on the topic do not venture far beyond the purely numerological aspect of the problem, namely finding numerical coincidences between sunspot periodicities, as inferred from Wolf's sunspot number time series, and the period of recurrence of this or that planetary configuration.[26]

In retrospect, Wolf's 1859 attempt is now seen to be far more ambitious, as he sought to fit not just the periods, but also the details of the amplitude variations in his sunspot number curve. In fact, over the years Wolf continued to work with variations along these lines, but without finding an acceptable solution. His final judgement on the matter is found in Part IV of his 1893 *Handbuch der Astronomie*, where he declares that none of the attempts, by himself or by others, to fit the sunspot number variations with models based on planetary influences, has produced truly satisfactory results.[27]

Ultimately, time would literally be the judge of these assorted variations on the planetary influence theme. Planetary motions are celestial clockwork, repeating themselves with inescapable Newtonian regularity, so that small differences in period have an inexorable *cumulative* effect, as is already apparent in Figure 2. By the turn of the century Wolf's historical reconstruction of the monthly sunspot numbers was generally considered reliable back to 1749, and the solar photographic monitoring program begun at Kew and continued at Greenwich covered over three full sunspot cycles. The data had reached a volume such that quantitative statistical analyses could be carried out to establish once and for all the reality — or lack thereof — of planetary influences on the solar cycle.

5. *Conjectures and Refutations*

Perhaps the most elaborate analysis of the planetary influence thesis after the Kew team was carried out in the late 1890s by the Norwegian physicist Kristian Birkeland (1867–1917).[28] Well into the twentieth century, Birkeland clung to the idea that the bulk of the Sun's volume is comprised of a solid nucleus in which "caves" filled with hot, molten material feed volcanic-like eruptions, which he assumed lead to the formation of sunspots as the erupting material disrupts the photosphere from below. Birkeland was actually trying to find support for this view in analysis of the sunspot data for possible planetary influences. His idea was that regular recurrences in the longitudes of sunspots should be present if they are ultimately due to one or more "volcanoes" co-rotating with the Sun's rigid nucleus. His first task is thus really to *refute* the planetary influence thesis, which would lead to similar longitudinal recurrences.

Working in the context of tidal models, he did so quite convincingly as far as the primary 11-year cycle is concerned, but ended up detecting hints of correlations between planetary ecliptical longitudes and heliocentric longitudes of large sunspot groups extracted from the Greenwich dataset for 1892–95. In this respect his approach and findings are in fact very much along the lines of Kew team's work, although differing in details. Faced with this (unwelcome) evidence for planetary influences on the timescale of months to years, Birkeland held on to his volcanic ideas as the primary causal agents for the formation of sunspots, while granting planetary tidal influences a possible triggering effect.[29]

Birkeland's unconventional views on the Sun's constitution likely contributed to the limited attention paid by the mainstream of Solar Physics to his extensive analysis of sunspot data, and to his firmly negative conclusions regarding planetary causes for the primary 11-year cycle period. As a matter of fact, the planetary influence thesis enjoyed a short-lived revival at the turn of the century, first in the hands of two established giants in celestial mechanics, Simon Newcomb (1835–1909) and Ernest William Brown (1866–1938). Brown's contribution[30] is not exceedingly original, as he merely sought, once again, to match Wolf's sunspot number time series with a combination of two periodic forcings, the first with period $P = 11.86$ years associated with Jupiter's orbital eccentricity, the second with period $P = 9.93$ years corresponding to the half-tidal period of Saturn. Yet his stature in the community was such that his work could not fail to attract attention.[31]

Newcomb's 1901 paper[32] is more substantial. Newcomb was not interested in planetary influences *per se*, but instead was using the sunspot number time series in an attempt to distinguish between two possible situations with regards to the sunspot cycle: (1) the mechanism underlying the cycle is a truly periodic phenomenon, over which are superposed purely random fluctuations arising from secondary causes; (2) the cycle itself is not strictly periodic, leading directly to the observed variations in its measured period. In the former case, sunspot minima (say) should recur at epochs $nP \pm \varepsilon$ after n cycles, where P is the true underlying period and ε the (presumably random) "phase error" introduced by secondary causes. This phase error is expected to have zero mean, and so should be statistically independent of n. In the latter case however, true variations in cycle duration add up as a random walk in apparent phase with respect to the mean period, and consequently the cumulative phase error grows as $\sqrt{n}$. Newcomb's analysis ended up favouring the first situation, and thus the existence of a truly periodic mechanism underlying the sunspot cycle.[33]

Newcomb was careful to add that his results are insufficient to decide whether the cause of the cycle is internal or external to the Sun. Yet, the clock-like regularity suggested by his analysis is precisely what one would expect from planetary influences, something that did not escape those of Newcomb's readers already favourably disposed toward the idea.

The next major salvo was fired by Arthur Schuster, and despite a half-century interlude, is characterized by an almost uncanny continuity with the Kew team.[34]

Arthur Schuster (1851–1934, see Figure 6) was born in Frankfurt, Germany. His family chose to move to Manchester in 1866, following the invasion of their homeland by Prussia. Originally destined to enter the family business, Schuster soon diverted his attention to Physics and Astronomy. In 1871 he entered Owens College and attended the Physics classes taught by Balfour Stewart, who had just joined the Faculty.

FIG. 6. Arthur Schuster (courtesy of Living Archives).

Schuster went on to obtain his Ph.D. in Heidelberg working with Gustav Kirchhoff (1824–87) and Robert Wilhelm Bunsen (1811–99), and eventually returned to Owens College in 1873 as demonstrator in the Physical Laboratories. He became professor of applied mathematics there in 1881, and in 1888 was elected to the Langworthy Professorship in Physics in succession to Balfour Stewart. Although he is remembered today primarily for his researches on radiative transfer and electrical discharge in gases, Schuster maintained an interest in Solar Physics throughout his career.

In order to be able to quantify the statistical significance of his analysis, Schuster chose to focus on the time and location of *first appearance* of sunspots, as a yardstick with which to assess hypothetical planetary influences.[35] Restricting his attention to spots having appeared within ±60° of the central meridian, he first extracted 4271 events from the 26-year-long Greenwich dataset then at his disposal. His overall approach to data reduction, illustrated in Figure 7, is in many ways a generalization

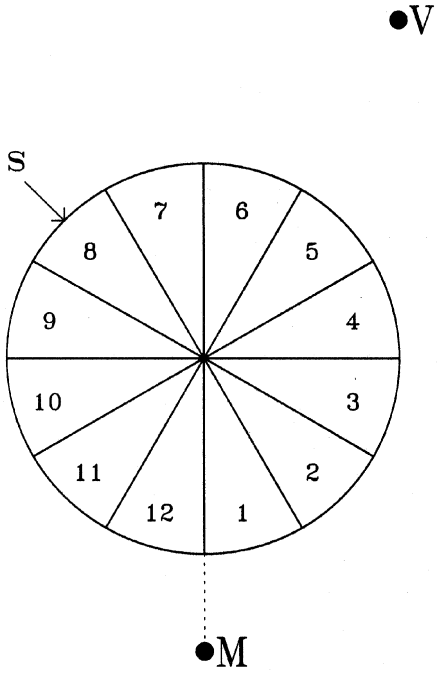

FIG. 7. Schuster's method for tabulating sunspot emergence. The Sun's surface is divided into 12 longitudinal sectors of angular width 30°. Sectors are numbered in the counterclockwise direction, starting from the line (dotted) joining a planet (**M**) to the solar centre. For example, a spot (**s**) emerging at the location indicated by the arrow would be accounted as belonging to Sector 8, from the point of view of **M**. From planet **V**, however, the emergence would be ascribed to Sector 3.

of the Kew team's procedure (*cf.* Figure 4). The solar surface is divided into 12 longitudinal sectors of width 30°, numbered counterclockwise, starting from the line segment joining a given planet (here **M**) to the Sun. As this sectorial grid co-rotates (counterclockwise) with the orbiting planet, appearing sunspots are assigned to the corresponding sector. The end result is a count (*N*) of sunspot appearances in each of the 12 co-rotating sectors. This procedure is carried out separately for Mercury, Venus, and Jupiter. As a control experiment, Schuster repeated the exercise with Mars and Saturn (from which he expected no effect), as well as with an arbitrarily selected fixed point in space, for which he chose the constellation Aries.

Schuster's Figure 2 is replotted herein as Figure 8, with the addition of $\pm\sqrt{N}$ error bars, and dashed lines indicating the mean count for each planet. Schuster actually began his discussion of results with the statement that for most sectors the deviations about the mean are comparable to what one would expect on purely statistical grounds

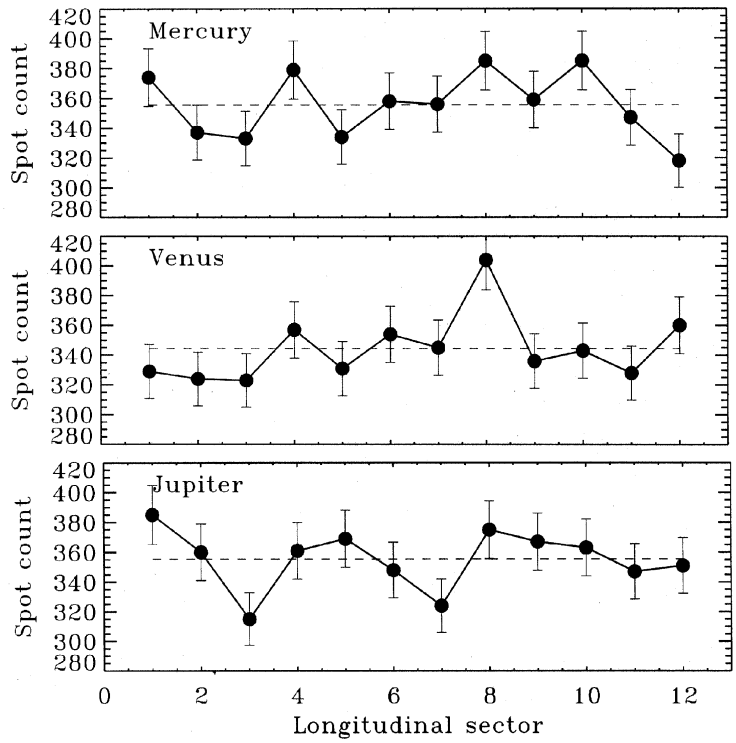

FIG. 8. Variations in the total number of sunspot appearances in longitudinal sector grids co-rotating with Mercury, Venus and Jupiter (see Fig. 7). The horizontal dashed line indicates the mean count, and the error bars indicate one standard deviation ($\sigma = \sqrt{N}$). Note how, in all but a few sectors, the data are within one standard deviation of the mean.

if sunspot appearances are uniformly distributed in heliographic longitude. The most important deviations occur in Sector 8 for Venus, and Sectors 3 and 7 for Jupiter. The Venus Sector 8 count is at the 3 standard deviations (3σ) level; the probability of random occurrence of a deviation larger than 3σ in any one of 12 statistically independent sectors is $p \approx 0.03$, if the data obey Poisson statistics. This is small, but Schuster knew all too well that he could not make a positive claim for planetary influences on this basis alone, especially since the average unsigned deviations about the mean counts for these three planets are no larger than for the "control group" consisting of Mars, Saturn, and Aries.

What Schuster did believe to be statistically significant is the similarity in the overall *shape* of the three curves. He was particularly struck by the fact that all three planets show a marked excess in Sector 8, and deficit in Sector 3. He then went on to compute the probability that these joint coincidences are due to chance alone, which he estimated at 1 in 400,000. The ever-cautious Schuster did not fail to add a crucial caveat: "The results of the above calculation might be seriously altered, if a number of groups of spots frequently occur simultaneously along the same meridian."[36]

Schuster's tentative conclusion was soon questioned by a similar piece of work carried out independently and more-or-less simultaneously by his fellow countryman F. J. M. Stratton (1881–1960). Stratton later achieved great professional status and left his mark in Solar Physics and stellar spectroscopy. However, in 1910 he was at the dawn of his career, having joined Cambridge Observatory in 1906 two years after graduating from Cambridge University.

Stratton was already familiar with sunspot data from his studies of their latitudinal drift, and his interest in planetary influences was originally spurred by a paper by Annie Maunder (1868–1947), pointing out a curious asymmetry in the statistics of sunspots when the data are subdivided in East and West hemisphere with respect to the solar central meridian.[37] Stratton's modelling approach follows closely Schuster's, except for his use of 24 sectors, each 15° wide. Like Schuster, he used the series of Greenwich solar photographs starting in 1874, but focused his attention on the possible effects of Venus and Jupiter only, and tried to correlate their ecliptical longitudes with either or both appearance and disappearance of sunspots.[38] Stratton showed that if the spot appearances (or disappearances) are first subdivided into solar northern and southern hemisphere spots and the analysis carried out independently for each data subset, the resulting curves are distinctly different in the two hemispheres, which is difficult to reconcile with the planetary influence hypothesis. Stratton also correctly pointed out that the sunspot dataset is not uniformly distributed in time, but rather is dominated by the years surrounding cycle maxima, which in itself can introduce systematic deviations about the mean spot counts for the superior planets, especially Jupiter. His conclusions regarding planetary influences are largely negative, although he still opted for caution by ultimately declaring the planetary influence hypothesis "Not Proven".[39]

Despite Stratton's rather sound counterarguments, Schuster's 1 in 400,000 figure was destined to be cited repeatedly in subsequent decades by later proponents of the planetary influence hypothesis. More often than not, however, his caveat cited above was conveniently forgotten; and therein precisely lay the key to the matter.

6. *The Fall*

Overall, the various statistical analyses carried out in the opening decade of the twentieth century had left the planetary influences thesis in a very precarious position. Its final downfall was precipitated by the landmark discoveries of George Ellery Hale (1868–1938) and collaborators at Mt Wilson Solar Observatory, who in 1908 demonstrated beyond doubt the magnetic nature of sunspots. In the following years they also established that sunspots often tend to occur in leading/following pairs of opposite magnetic polarities, approximately aligned with the E–W direction; that the polarities of these pairs are inverted between the Northern and Southern solar hemispheres; and that this polarity pattern reverses from one sunspot cycle to the next.[40] Hale *et al.* thus showed that the sunspot cycle is the manifestation of an underlying magnetic cycle having twice the period of the sunspot cycle. These results strongly suggested that the cycle is a hydromagnetic phenomenon operating within the solar interior, and ultimately were to relegate theories of planetary influences to the status of historical curiosity that they enjoy today.

That sunspots occur in pairs of opposite polarities led to the realization that these pairs represent the photospheric manifestation of a deep-seated toroidal magnetic flux system, developing growing undulations along its length until the apices pierce the surface, with sunspots forming where the flux ropes intersects the photosphere.[41] With regard to the planetary influence studies described above, the most important consequence of this state of affairs is that sunspots appearances are not all statistically independent. For example, Schuster's numbers should be divided by two to account for this pairing effect, which greatly reduces the statistical significance of his results.[42] The situation got even worse in view of the subsequent realization that the toroidal magnetic flux system might undergo fragmentation prior to its emergence, so that, over timescales of many days, sunspot appearances tend to recur in the vicinity of existing sunspot groups.[43] This further reduced the number of statistically independent sunspot appearances in Schuster's dataset, and effectively did away with any remaining significant probability of planetary influence.

Thus the thesis of planetary influences on sunspots was refuted in the opening decades of the twentieth century. However, it proved to be a very resilient idea, and papers on the topic continue to be published in 'reputable refereed scientific journals'. Some do offer new twists on arguments put forth in the nineteenth century, and so are not without (academic) interest. Most, however, simply repeat or rediscover the ideas and variations described herein. Few reach a level of data modelling sophistication comparable to Birkeland, Schuster, Stratton, or even the Kew team. Here as on the silver screen, the sequels are just never as good as the original.

Acknowledgements

I wish to thank Peter Hingley (RAS/London), Peter Hoyng (SRON/Utrecht), Egil Leer (University of Oslo), Robin Marshall (University of Manchester), and Jan Stenflo (ETH/Zürich) for their kind assistance in securing assorted biographical information on the various players in the foregoing story. Critical reading of an earlier draft by Tom Bogdan (HAO/NCAR), Steve Shore (University of Indiana/South Bend), and Andy Skumanich (HAO/NCAR) is also gratefully acknowledged. Special thanks are due to the staff of the NCAR Library, in particular Judy Litsey, for going beyond the call of duty in fulfilling my numerous interlibrary loan requests for old or hard-to-find material. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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1. Extract of a letter by the French astronomer Jérôme de La Lande (1732–1807) to fellow astronomer Franz Xaver von Zach (1754–1832), who reprinted it in his 1798 Ephemerides. “Seit 40 Tagen war nicht der geringste Flecken in der Sonne zu sehen, welches mir noch nie vorgekommen ist. Es ist doch zu verwundern, das zu gewissen Zeiten diese Licht-Materie die ganze Oberfläche des Sonnenkörpers überströmen und bedecken kann, und dass zu anderen Zeiten nicht genug dazu vorhandern ist; oder treibt eine Ebbe und Fluth diese Materie nach den Polen zu? welches mag wohl der Weltkörper seyn, der solche ungeheure Revolutionen auf der Sonne bewirken, und ihr so nahe kommen kann?” La Lande believed sunspots to be dark mountainous “islands” emerging above an “ocean” of luminous matter, so that the tides analogy probably imposed itself rather naturally upon him.
2. See D. V. Hoyt and K. H. Schatten, *The role of the Sun in climate change* (Oxford, 1997), 30. As noted by these authors, and especially given his favourable prejudice on the matter, it is indeed surprising that Horrebow did not discover the sunspot cycle sometime in the early 1770s, as the cycle stands out rather clearly in his dataset. Entries in Horrebow’s notebook for 1776, the year of his death, also indicate that he had begun to contemplate some sort of relationship between planets and sunspots: “Es ist indeβ zu hoffen, daβ man durch eifriges Beobachten auch hier eine Periode auffinden werde, wie in den Bewegungen des übrigen Himmelskörper; dann erst wird es an der Zeit sein zu untersuchen, in welcher Weise die Körper, die von der Sonne getrieben und beleuchtet sind, durch die Sonnenflecken beeinfluβt werden” (Rudolf Wolf, *Geschichte der Astronomie* (Munich, 1877), 654).
3. Heinrich Schwabe, “Sonnen-Beobachtungen im Jahre 1843”, *Astronomische Nachrichten*, no. 21 (1843), cols 234–6.
4. A. J. Meadows, *Early solar physics* (Oxford, 1970), 32–47, provides a lively description of these various ideas, and of the sometimes heated debates they generated.
5. Richard Christopher Carrington, *Observations of the spots on the Sun* (London, 1863), 1.
6. Originally published as: Rudolf Wolf, “Mittheilungen über Sonnenflecken VIII”, *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich*, iv (1859), 183–205.
7. Wolf used mid-nineteenth-century orbital data and, more importantly, perihelion distances to set the relative amplitude of each planet’s contribution; this explains the slight differences between his adopted amplitudes and the m/a^2 values listed in Table 1.
8. Carrington, *op. cit.* (ref. 5), 247.
9. Carrington, *op. cit.* (ref. 5), 248.
10. P. G. Tait, “Obituaries: Balfour Stewart”, *Proceedings of the Royal Society of London*, xlvi (1889), pp. ix–xi, p. ix.
11. Balfour Stewart, “On sun-spots and their connection with planetary configurations”, *Transactions*

of the Royal Society of Edinburgh, xxiii (1864), 499–504; although Stewart failed to identify a significant similar effect by Jupiter, he nonetheless endorsed what he interpreted to be Carrington's suggestion that Jupiter's heliocentric distance influences sunspot formation. That same year, Stewart published a second paper (Balfour Stewart, "On the large sun-spot period of about 56 years", *Monthly notices of the Royal Astronomical Society*, xxiv (1864), 197–8), pointing out that Jupiter and Saturn come close to aphelion simultaneously every 59 years, which is interestingly close to the 56-year sunspot periodicity suggested by Wolf a few years earlier.

12. Warren De La Rue, Balfour Stewart and Benjamin Loewy, "Researches on solar physics. Second series. On the behaviour of sun-spots with regard to increase and diminution", *Proceedings of the Royal Society of London*, xiv (1865), 59–63.
13. Warren De La Rue, Balfour Stewart and Benjamin Loewy, "On the distribution of solar-spotted area in heliographic latitude", *Monthly notices of the Royal Astronomical Society*, xxvii (1866), 12–14.
14. Warren De La Rue, Balfour Stewart and Benjamin Loewy, "Researches on solar physics. No. II", *Philosophical transactions of the Royal Society of London*, clx (1870), 389–496; they had first inferred a similar trend involving the Jupiter-Venus and Mars-Mercury pairs ("Kew Observatory", *Monthly notices of the Royal Astronomical Society*, xxx (1870), 92–94), but this evidently failed to hold as more data were analysed.
15. Warren De La Rue, Balfour Stewart and Benjamin Loewy, "Further investigations on planetary influence upon solar activity", *Proceedings of the Royal Society of London*, xx (1872), 210–18; this is in fact a 9-page extended abstract of a much lengthier work, which was never published for reasons soon to be discussed.
16. De La Rue, Stewart and Loewy, *op. cit.* (ref. 15), 213–17.
17. De La Rue, Stewart and Loewy, *op. cit.* (ref. 15), 212.
18. De La Rue, Stewart and Loewy, *op. cit.* (ref. 15), 216.
19. Arthur Schuster, "The influence of planets on the formation of sun-spots", *Proceedings of the Royal Society of London*, xxxv (1911), 309–23. In later writings, Schuster is even more explicit, e.g.: "[Loewy] saved himself trouble, and evolved the results out of his inner consciousness" (Arthur Schuster, *Biographical fragments* (London, 1932), 213).
20. This paper was to be the full-length version of the 1872 extended abstract discussed above. The whole episode is recalled by Schuster in his aforecited *Biographical fragments*, which also includes an account of the events leading to Stewart's resignation from Kew. Schuster's choice of words in the 1911 extract cited in the text, "... which it would be wrong now to conceal...", suggests that Loewy's sins were not immediately publicized following their discovery. Up to February 1873 the sunspot investigations by "Messrs. De La Rue, Stewart and Loewy", including planetary influence studies, are reported upon matter-of-factly in the Kew Observatory report included in the minutes for the Annual General Meetings of the Royal Astronomical Society. Then, in the minutes of the 54th Annual General Meeting, one reads: "Some unforeseen interruption has occurred in the measurement and discussion of the Sun-spots, which will cause a delay of two years in the publication of the results. Arrangements are being made for the micrometrical measurements to be conducted at Kew Observatory, and the work will be completed as soon as possible by Messrs. De La Rue and Balfour Stewart" ("Kew Observatory", *Monthly notices of the Royal Astronomical Society*, xxiv (1874), 163).
21. In some papers published in the late 1870s, Stewart did investigate possible correlations between planetary configurations and variations in terrestrial magnetism, in the course of which he mentions some of his pre-1872 sunspot-related results, without however commenting on the 1872 events. See, e.g., Balfour Stewart, "On the variations of the daily range of the magnetic declination as recorded at the Kew Observatory", *Proceedings of the Royal Society of London*, xxvi (1877), 102–21; and Balfour Stewart, "On the diurnal range of the magnetic declination as recorded at the Trevandrum Observatory", *ibid.*, xxvii (1878), 81–88.
22. See, for example, J. Norman Lockyer, *Contributions to solar physics* (London, 1874), 386. A. Secchi's *Le Soleil* (Paris, 1875), 188–93, is somewhat more cautious in its assessment, even though the Kew team's work formed the centrepiece of Secchi's discussion of the possible causes of the

sunspot cycle.

23. Another early proponent of this latter class of model was the American physicist Pliny Earle Chase (1820–86), who attempted to associate the waxing and waning of sunspots with the position of the solar system's centre of mass. See Pliny Earle Chase, "The sun-spot cycle of 11.07 years", *Proceedings of the American Philosophical Society*, xxii (1872), 410–11; and Pliny Earle Chase, "Planetary relations to the sun-spot period", *ibid.*, xxiii (1873), 147–8. This variation was destined to be rediscovered repeatedly in the course of the twentieth century.
24. The possibility of *magnetic* influence between the Sun and planets was also considered to be a plausible mechanism, as mid-nineteenth century solar physicists began to contemplate the possibility that the Sun, like Earth, is magnetized. From 1852 onwards, Rudolf Wolf repeatedly alluded to this possibility in his writings. The American astronomer Francis E. Loomis, although primarily interested in variable stars, also discussed the idea in the introductory chapter of his inaugural doctoral dissertation entitled "Periodic stars" (Göttingen University, 1869), where he went on to propose that the small difference between the sunspot period and Jupiter's orbital period could perhaps be accounted for if the solar magnetic axis, like Earth's, undergoes secular variations in its orientation.
25. Hoek wrote: "Qu'on se représente des conditions d'équilibre instable, et la moindre force suffit à le rompre et à produire des phénomènes importants. Dans le cas actuel il n'est pas impossible de se représenter de telles circonstances. Les couches extérieures du Soleil, rayonnant leur chaleur dans l'espace, doivent par conséquent devenir plus denses. Il suffit que leur densité surpasse celle des couches situées plus près du centre pour avoir l'équilibre instable. Il viendra un moment où elles iront s'engloutir dans l'intérieur du Soleil pour être remplaçées par des couches moins denses. Il est donc possible que les marées produites par les planètes, quelque insignifiantes qu'elles soient, suffisent à fixer ce moment" (extract from a letter to De La Rue, dated 26 January 1867, and published as M. Hoek, "Considerations on sunspots", *Monthly notices of the Royal Astronomical Society*, xxvii (1867), 208–11). The American solar physicist Charles A. Young (1834–1908) was to echo similar thoughts as late as the 1897 revised edition of his popular Solar Physics textbook (Charles A. Young, *The Sun* (New York, 1897), 159), although the general tone of his discussion makes it clear that he did not give great credence to the overall issue of planetary influence on sunspots.
26. See Nils Ekholm, "Ueber die Periodicität des Sonnenthätigkeit", *Bihang till Kungliga Svenska Vetenskapsakademiens Handlingar*, xxv (1901), 1–71, for a fair, critical review of many of these attempts; and Émile Anceaux, "Sur la corrélation des taches et des marées du soleil", *Bulletin de la Société Astronomique de France*, xix (1905), 73–78, for a reasonably succinct account of a multi-planet tidal model, including orbital eccentricity effects.
27. "Zum Schlusse mögen noch die von mir und andern gemachten Versuche erwähnt werden, die Coordinaten der Fleckenkurve durch Formeln darzustellen, oder den Verlauf der Erscheinung durch eine Art Rückwirkung der Planeten auf die Sonne zu erklären, obschon dieselben bis jetzt noch nicht zu ganz befriedigenden Resultaten geführt haben", Rudolf Wolf, *Handbuch der Astronomie, ihrer Geschichte und Litteratur, Band IV* (Zürich, 1893), 410.
28. Kr. Birkeland, "Recherches sur les taches du soleil et leur origine", *Videnskabs selshabets skrifter* (Christiania, 1899), 124.
29. "Le résultat négatif auquel nous sommes arrivés en ce qui concerne la période undécennale n'a d'ailleurs aucune influence sur nos résultats, à l'égard des variations de courte période, et n'infirment donc pas l'hypothèse, suivant laquelle les forces perturbatrices exercées sur le soleil par les planètes est à même de donner le branle à la production des taches et d'imprimer un certain rythme aux éruptions qui ont lieu sur le Soleil" (Birkeland, *op. cit.* (ref. 28), 125).
30. Ernest W. Brown, "A possible explanation of the sun-spot period", *Monthly notices of the Royal Astronomical Society*, lx (1900), 599–606.
31. Birkeland immediately revisited his 1899 calculations in the light of Brown's paper, only to reiterate *verbatim* his earlier negative conclusion, however (Kr. Birkeland, "Les taches du Soleil et les planètes", *Comptes rendus de l'Académie des Sciences*, cxxxiii (1901), 726–9). Nonetheless, whenever discussing his own theory of the sunspot cycle, he continued to mention planetary

influences as a plausible alternative; see, e.g., Kr. Birkeland, "Recherches sur les taches du soleil et leur origine", *Memorie della Societa degli Spettroscopisti Italiani*, xxiv (1905), 14–18.

32. Simon Newcomb, "On the period of the solar spots", *The astrophysical journal*, xiii (1901), 1–14.
33. The analysis is more complex than suggested by this brief sketch, in view of the impossibility of estimating the mean period independently of the data being tested. The issue of phase memory was revived by R. H. Dicke in the late 1970s (see R. H. Dicke, "Is there a chronometer hidden deep in the Sun?", *Nature*, cclxxvi (1978), 676–80; also R. H. Dicke, "The phase variations of the solar cycle", *Solar physics*, cxv (1988), 171–81), and continues to befuddle solar physicists to this day; see, e.g., Paul Charbonneau and Mausumi Dikpati, "Stochastic fluctuations in a Babcock-Leighton model of the solar cycle", *The astrophysical journal*, dxliii (2000), 1027–43.
34. In saying so it is not at all my intention to belittle Schuster's contribution to the problem. But after working through the writings of the Kew team, Schuster's paper reads very much like Balfour Stewart's final *tour de piste*, relayed from beyond the pale by his former pupil, colleague, and successor at Owens College.
35. Arthur Schuster, "The influence of planets on the formation of sun-spots", *Proceedings of the Royal Society of London*, lxxxv (1911), 309–23. A few years earlier, using his newly developed periodogram technique, Schuster had carried out a careful analysis of the Wolf sunspot number and Greenwich sunspot area time series (Arthur Schuster, "On the periodicities of sunspots", *Philosophical transactions of the Royal Society of London*, ccvi (1906), 69–100). Where Wolf and others had been *assuming* planetary-related periodicities and adjusting other model parameter to fit the data, here Schuster was extracting periodicities from the data, and comparing them to periodicities extracted in a similar way from the sunspot number time series. Whether at the synodic or sidereal orbital periods, he had not found any significant signal in the periodograms for either Mercury, Venus, or Jupiter. Yet he evidently felt compelled to revisit the problem.
36. Schuster, *op. cit.* (ref. 35), 317.
37. A. S. D. Maunder, "An apparent influence of the Earth on the numbers and areas of sun-spots in the cycle 1889–1901", *Monthly notices of the Royal Astronomical Society*, lxvii (1907), 451–75. This curious hemispheric effect was already mentioned in the Kew team's 1872 paper and in Birkeland's 1899 tome, has shown up in later studies, and remains unexplained to this day.
38. F. J. M. Stratton, "On possible phase-relations between the planets and sun-spots phenomena", *Monthly notices of the Royal Astronomical Society*, lxxii (1911), 9–26.
39. Stratton, *op. cit.* (ref. 38), 26. Interestingly, Stratton concluded his paper by reiterating his belief in the possibility of planetary influences on the Sun in much the same language as his nineteenth-century predecessors: "... the dynamical effects of planets upon what may be an atmosphere of very uncertain stability should be manifested in some solar phenomena" (*ibid*).
40. See George E. Hale, "On the probable existence of a magnetic field in sun-spots", *The astrophysical journal*, xxviii (1908), 315–43, and George E. Hale *et al.*, "The magnetic polarity of sun-spots", *The astrophysical journal*, xlix (1919), 153–78.
41. See, e.g., Eugene N. Parker, "The formation of sunspots from the solar toroidal field", *The astrophysical journal*, cxxi (1955), 491–507. This is sometimes referred to as the "sea-serpent" model of sunspot emergence, and has been amply vindicated by subsequent observational and modelling work.
42. For example, on an appropriately revised version of Figure 8, the Venus sector 8 count becomes a 2σ effect ($p = 0.33$ for chance occurrence in any one of 12 sectors), and the excesses in Mercury's Sectors 3 and 8 fall back to the 1σ level.
43. On these so-called "sunspot nests" see, e.g., Constance Sawyer, "Statistics of solar active regions", *Annual review of astronomy and astrophysics*, vi (1968), 115–34; M. J. M. Castenmiller, C. Zwaan and E. B. J. van der Zalm, "Sunspot nests", *Solar physics*, cv (1986), 237–55; M. P. Brouwer and C. Zwaan, "Sunspot nests as traced by a cluster analysis", *Solar physics*, cxxix (1990), 221–46. The existence of "active longitudes", regions of recurrent sunspot activity persisting for many sunspot cycles, remains a topic of debate; see, e.g., M. Neugebauer *et al.*, "The solar magnetic field and the solar wind: Existence of preferred longitudes", *Journal of geophysical research*, cv (2000), 2315–24, and references therein.