



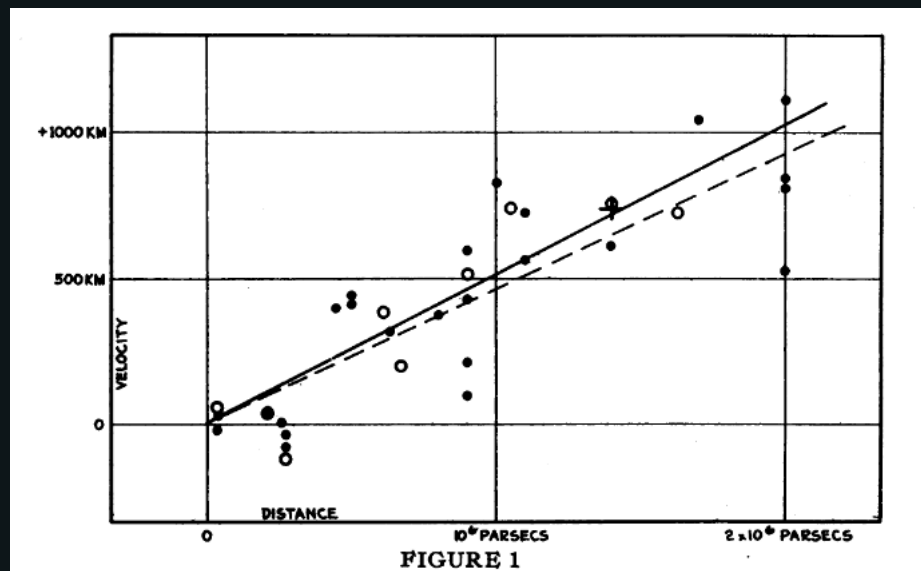
BULLETIN

ISSUE 42 AUTUMN 2024

The Venus Tablet of Ammisaduqa

Mad Jack's Observatory

Celebrating Edwin Hubble



Issue 42 Autumn 2024

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Front cover: *Original plot of radial velocity-distance relation for galaxies, published by Edwin Hubble in his 1929 paper (DOI: 10.1073/pnas.15.3.168, page 172). (Wikimedia Commons.)*

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EDITORIAL

It is certainly not always the case that new developments are immediately appreciated. The laser is a good example, with inventor Theodore Maiman allegedly describing it as “a solution looking for a problem”. In this issue of *The Bulletin*, we read of several examples where the building of an instrument, the taking of a measurement or the keeping of a record made a long-lasting impression, the importance of which only became significant and fully appreciated some time later.

In what may be called the centenary year of the Hubble-leMaître law (as it became known), it is all too easy to take the Big Bang theory and the accepted structure of the cosmos for granted and consider it an old and well-established idea. But History can be surprisingly recent.

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The time is out of joint: Louis Essen, Atomic Time and the demise of the Royal Greenwich Observatory

Timothy Baker

This is the second instalment of a two-part article. The first part is in Bulletin 41 and described the development of quartz clocks, and of the world's first atomic clock, 'Cs-1' in 1955, by Louis Essen of the National Physical Laboratory (NPL).

The International Astronomical Union (IAU) meeting of 1950 saw the proposal of the 'ephemeris second'—designed by Gerald Maurice Clemence (1908–1974), of the US Nautical Almanac Office, and based on the duration of the Earth's annual orbit around the Sun, and thus the Sun's movement against the fixed stars—to replace the previous definition of the second, measured on the basis of the daily rotation of the Earth on its axis. The ephemeris second thus aimed to eliminate the variations in the second from year to year arising from the gradual slowing of the Earth's rotation by tidal friction, and other slight irregularities in the Earth's rotation on its axis. However, the duration of the year also diminishes, albeit regularly, by about half a second per century. So the accurate definition of the ephemeris second would rely on several years' observations of the Earth's orbit around the Sun, whereas engineers and physicists needed an immediately available standard. Louis Essen argued that the IAU should delay its decision on the definition of the second pending the outcome of research on atomic time, but IAU pressed ahead in 1952, and the International Committee for Weights and Measures concurred, but with the proviso that atomic time would be introduced once an accurate comparison of it with the ephemeris second was completed.

Central to the story of the new methods of finding time, and of NPL's replacement of RGO, was one

man, whose brilliance not only eclipsed the RGO's but was also central to the redefinition and recalibration of international standards themselves, not only of time, but of other physical quantities as well. Louis Essen (1908–1997), son of a Nottingham bootmaker, educated at High Pavement School and University College, Nottingham, who worked at NPL from 1929 to 1972, played a central role in the development of quartz clocks and atomic clocks; the precise measurement of the speed of light and of the second; the redefinition of the second as an atomic quantity and of the speed of light as an atomic standard underlying most other physical measures; and the development of mechanisms for precise coordination of the accuracy of the atomic second and of atomic time worldwide.

NPL began transmitting atomic time and frequency standards based on Essen's pioneering atomic clock, Cs-1, from 1955, which RGO used to calibrate its quartz clocks and time signals (Figure 1). 1955 was thus effectively the beginning of the atomic time standard, though it took many years to agree it formally and internationally. From 1956 Essen strongly advocated replacing the ephemeris second with an atomic frequency standard, and corresponding fundamental atomic second.

In 1955–1958, with William Markowitz (1907–1998) of the United States Naval Observatory (USNO) in Washington DC, a pupil of Isidor Rabi, Essen conducted intensive measurements, over



Figure 1: Mk. 1, the first caesium atomic clock from the National Physical Laboratory (NPL) in London from 1955, on display in the Science Museum in London (Wikimedia Commons).

conducted intensive measurements over three years, to compare the caesium transition frequency to the new ephemeris second. Essen had met Markowitz, who had acquired Essen ring quartz oscillators for the standard clocks at USNO, in a 1953 visit to the USA. Essen's and Markowitz's collaboration made two comparisons, one on each side of the Atlantic Ocean. Monthly over the three years, Essen used Cs-1 to measure the number of caesium transitions in the UT2 second, as transmitted by the National Bureau of Standards' (NBS) 'WWV' station from Greenbelt, Maryland, determined from UT2 time. UT2, which corresponded with the Royal Greenwich Observatory's (RGO) Provisional Uniform Time (PUT), introduced in 1953, was a (variable) mean time determined from stellar transits, smoothed to even out slight variations caused by 'polar wandering' and seasonal effects. USNO determined UT2 from measurements of stellar positions made by Frank Elmore Ross's Photographic Zenith Tubes (PZTs) at Gaithersburg and Richmond, Florida. Though they dated back to 1910, these instruments were accurate to within 10 milliseconds of time. At this time RGO at Herstmonceux was still installing Dudley Perfect's improved PZT, accurate to within 1 millisecond, so it was not

yet ready to assist the research. While Essen was measuring the atomic length of the UT2 second, Markowitz set out to measure the ephemeris second against the UT2 second. To do so he used his 'moon clock' which, as a proxy for the annual movement of the Sun that was the basis for ephemeris time, measured the intervals between the Moon's occultation of stars. The 'moon clock' was an ingenious device which, by using a tilting filter to obscure the Moon, enabled precisely timed simultaneous photographs of both the Moon and the occulted stars. It could provide both the right exposure for a simultaneous image of the bright Moon and the faint occulted stars, and a sharp image over several seconds of both the Moon (moving eastwards against the fixed stars at about 0.5 arcseconds per second), and the stars (moving westwards with the heavens at 15 arcseconds per second). Consolidating their data, Essen and Markowitz were thus able to compare the atomic second with the ephemeris second.

In 1958 at the Moscow meeting of the IAU, Essen and Markowitz announced their result, showing an unexpectedly rapid slowing of the Earth's rotation, much faster than the slowing attributable to the

tides (later it was shown to be part of an irregular speeding or slowing of the rotation probably caused by movements of masses in the Earth's interior). As a result the UT2 second was (in 1955–1958) steadily lengthening. In contrast, Essen and Markowitz showed that the ephemeris second was constant. This result led to the provisional adoption of the atomic second as a unit of time, representing the value of the ephemeris second in terms of the frequency of microwave radiation arising from the quantum oscillation of the spectrum of caesium 133 between its hyperfine ground energy states, at 9 192 631 770 hertz. The definition of the atomic second thus 'fossilised' the astronomical ephemeris second, which had been determined according to the average duration of the solar day over the 18th and 19th centuries, with Ephemeris Time set close to Universal Time at the beginning of 1900. By the 1950s the mean solar day had lengthened, so UT2 was running some 30 seconds behind Ephemeris Time. Various attempts were made to resolve the discrepancy by adjusting the length of the UT2 second, or by introducing periodic corrections to keep Ephemeris Time in line with UT2 time.

Essen resisted proposals from astronomers to establish separate definitions of the second for astronomical and civil purposes (a unit name of 'essen' was proposed for the latter) because of the confusion and duplication that would result.

The ease of finding atomic time from an atomic clock, by comparison with the laborious and retrospective process of computing the UT2 second, underlay the International Committee for Weights and Measures recommendation in 1963 to adopt the atomic second as the standard, and it was used to define the ephemeris second internationally from 1964. In 1968 the International Bureau of Weights and Measures redefined the SI second as a purely atomic standard, independent of astronomy, based on the measurements made by Essen and Markowitz with Cs-1. This precise definition of the SI second - to one part in 100 000 000 000 000: the most precisely measured SI unit - was also adopted by the IAU for astronomical purposes in 1968 (RGO alone abstaining from the IAU vote).

Essen later advocated replacing a wavelength in the optical spectrum of krypton, subject to experi-

mental error, which from 1960 was used to define the metre, with a system based on the far more accurately measurable frequency of atomic transitions. He advocated defining the speed of light arbitrarily by reference to a specified frequency of atomic transitions, and then using it to define the length standard by reference to the atomic time taken by light to traverse it, as the International Bureau of Weights and Measures did in 1983. From 1991 the IAU duly determined that the measurement of distances be by reference to the time taken by light to traverse them at its defined speed.

In the late 1960s atomic clocks were accurate to 1/1 000 000 000 000: 10 000 times more accurate than astronomical measures. The precision of measurement of time and frequency increased roughly tenfold in every decade after the Second World War. Essen's second has in turn become the fundamental basis for determining all other SI units, both mechanical and electrical, related to it by precise quantum phenomena.

The arrival of both quartz and atomic clocks enabled detailed studies of short-term variations in the length of the day, which in the period since 1960 has varied within a range of about 3 microseconds.

Synchronising frequency standards and time signals; the decline and demise of the Royal Greenwich Observatory

Another problem needing to be resolved was how to synchronise atomic clocks internationally. The time of receipt of Very Low Frequency (VLF) transmissions across the Atlantic could be measured only to a precision of +/- 2000 microseconds. Side-by-side comparisons showed that NPL and USNO atomic clocks ran at different rates. The collaboration of Essen with John Alvin (Jack) Pierce (1907–1996) of Harvard University, a specialist in the use of radio signals for air and sea navigation, was the culmination of a process of synchronisation of worldwide time that dated back to the era of clockwork chronometers and lunar distance measurements.

The first automatic coordination of timescales at a distance by the Royal Observatory was in response

to the need for coordination of railway timetables: GMT, transmitted electrically from Charles Shepherd's electric clock at Greenwich via the electric telegraph, replaced local time across the United Kingdom from 1852. The Statutes (Definition of Time) Act, 1880 established GMT as the legal time for England and Wales and Scotland. The need of ocean navigation for coordinated worldwide time in order to measure longitude resulted in the Washington Conference of 1884 that defined Greenwich as the Prime Meridian of the World. From the early 20th century GMT, corresponding to the Universal Time introduced for astronomical purposes from 1928, was maintained consistently across the world to an accuracy of 1 second. The BBC broadcast the Pips time signal, controlled by Greenwich, from 1924. The General Post Office (GPO) transmitted a time signal globally for navigators on behalf of the Royal Observatory from 1927. To improve accuracy, from 1938 time signals began to be based on the mean time shown by clocks at a range of different locations (initially Shortt clocks at Greenwich, Teddington, and Edinburgh, soon replaced by quartz clocks), compared by radio signals between them.

From 1926 NPL made the first experimental transmission of standard frequencies, for Edward Appleton's research on the ionosphere. In the 1930s Essen showed that transmitted frequency standards could be compared internationally to an accuracy of 2 parts in 100 000 000. Frequency transmissions from the UK ceased in 1939. After the war Humphry Montague Smith (1913–2005), head of the Royal Observatory's Time Department, and Harold Spencer Jones (1890–1960), Astronomer Royal, pressed for the Royal Observatory to transmit standard frequencies alongside its time service, but the Admiralty, the government department responsible for the Royal Observatory, was not prepared to fund it. Appleton, now Secretary of the Department of Scientific and Industrial Research (DSIR), eventually allocated the responsibility for transmitting frequency standards to NPL, with DSIR funding. This decision paved the way for NPL eventually to take over responsibility for time determination from RGO too, part of the erosion of its traditional functions that helped to undermine its status and eventually to precipitate its closure. From 1950 GPO, on behalf of NPL, transmitted the 'MSF' signals at 60 kHz, and 2.5, 5, and 10 MHz from Rug-

by across Britain and north-west Europe, controlled by the Essen ring quartz clock.

In 1953 Essen visited Jack Pierce at Harvard. Essen suggested that Pierce try to receive the 60 kHz MSF transmission from Rugby, which, to his surprise, he was able to do. Essen and Pierce used the Rugby GBR 16 kHz signal to compare the frequency of quartz clocks in the UK and USA, to an accuracy of 1 part in 10 000 000 000. A global navigation system required more stable clocks: Rugby's transmission of atomic time from 1955, and the installation of atomic clocks in the USA from 1956, enabled their first transatlantic comparison on 1956 November 16. Atomic clocks manufactured by Airmac Limited of High Wycombe, Buckinghamshire, combined with frequency-divider-controlled quartz clocks, made it possible for GPO to provide a stability of 1/10 000 000 000 in frequency standard transmissions.

Following up this research, Essen used VLF radio transmissions of atomic time from Rugby to promote international convergence of time standards. GBR signals from Rugby, controlled by NPL's Essen quartz ring oscillators, were used from 1954 for worldwide naval communications. Essen and Pierce led research to design methods accurately to synchronise atomic clocks separated from each other by thousands of miles. RGO and USNO joined in Essen's and Pierce's work on synchronisation of transmissions, which resulted in 1960 in the replacement of GMT/UT by Coordinated Universal Time (UTC), a joint enterprise of NPL, RGO, USNO, NBS, and the US Naval Research Laboratory.

From the 1950s onwards, NPL researched coordinating time signals at higher, microwave frequencies, using satellite reflections to transmit across the Atlantic, thereby eliminating inaccuracies resulting from variations in the ionosphere. With the launch of Echo-1, a large silvered balloon, the USA's first artificial satellite, in 1960, NPL attempted unsuccessfully to track reflections of signals from the USA. But with Telstar-1, the first active communications satellite, launched in 1962, experiments showed it was possible to synchronise clocks transatlantically within 1 microsecond. There was an international programme of side-by-side comparisons of atomic clocks from 1964 to 1967, using the

first portable atomic clock, made by Hewlett Packard. NPL's own portable clock, transported by air to observatories around the world for six-monthly comparisons, was still large enough to need its own passenger seat, booked in name of 'Mr P Clock (P for 'precision', to avoid using the touchy word 'atomic'). This work led to an internationally synchronised time service, the International Time Bureau's International Atomic Time (TAI) from 1972, and to Pierce's Omega navigation system, accurate to 1 nautical mile, based on triangulation from 8 transmitters worldwide, operational from 1968, and the forerunner of the modern Global Positioning System and Galileo Navigation System.

Though it had provided an atomic time scale based on signals from NPL and GPO from 1955, RGO acquired its first atomic clock (a Hewlett-Packard 5060A) only in 1966, using it, with NPL data, to publish a formal Greenwich Atomic (GA) timescale. From 1968 RGO published the GA2 timescale, based exclusively on its own atomic clocks, using it as input to the continuing electromechanical system for producing the six 'Pips' time signal; and to contribute to TAI. From 1972 the Pips gave UTC, no longer GMT, which had already been abolished for scientific purposes in the 1920s, and passed into a legal limbo, continuing to be the legal time in the UK, de-

spite an attempt by the House of Lords in 1997 to move the country officially to UTC, which, in the words of Tony Jones (*Splitting the Second*, 2000), foundered because it 'ran out of time' in the House of Commons [1].

The only remaining astronomical involvement in the determination of time was the 'leap second' adjustments, implemented as needed to keep clocks in line with small variations in the Earth's movement relative to the heavens. The leap second, a compromise suggested by Essen and Gernot Winkler (1922–2016) of USNO to resolve the discrepancy between the needs of astronomers (UTC) and of engineers (TAI), was implemented as needed from 1972. A seventh pip would be introduced to the midnight Pips to mark leap seconds. But RGO even ceased to be responsible for leap seconds when radio methods replaced its PZT for this purpose in 1984.

Jones [2], and Essen [3] in *Revolutions in Time*, speculated on whether astronomers might have been able to retain more control over time determination had pulsars been discovered by radio astronomy a decade earlier than they eventually were, by Jocelyn Bell Burnell at Cambridge in 1967.



Figure 2: The meridian laser at the Royal Greenwich Observatory, 2006 (Markhamilton, English Wikipedia).

In the 1980s, it was suggested that pulsars, regularly spinning magnetic stars which emit radio pulses the stability of whose frequency is comparable to atomic frequency standards, might even be able to provide a more stable time scale than atomic clocks. Astronomical Universal Time had been fighting a losing battle with atomic time since 1955, and atomic clocks were always going to be a more convenient frequency standard, but it is a nice 'what if' to wonder, as Jones did, what might have happened had IAU been in a position to replace Universal Time with pulsar time rather than the hard-to-determine Ephemeris Time.

Accurately synchronised and compatible atomic clocks went on to become an essential element of the operation of electronic information technology and the transfer of data worldwide. As Sir Alan Cook, Essen's biographer in *Biographical Memoirs of Fellows of the Royal Society*, 1998, observed of him: 'A rare mind, he left us a different world' [4].

Wartime dislocation, and the long-drawn-out move from Greenwich to Herstmonceux, had disrupted the Royal Observatory's work. Successive Astronomers Royal Harold Spencer Jones and Richard Woolley (1906–1986) resisted Humphry Smith's efforts to develop its astronomy into radio and other non-optical bands of the electromagnetic spectrum, and to conduct British research on satellite navigation. The post-war stringency and run-down of the Royal Navy, and the folding of the Admiralty, the RGO's paymaster, into a consolidated Ministry of Defence in 1964, deprived RGO of a steady and reliable source of funding. From 1965 RGO came under the aegis of the DSIR's new replacement, the cross-disciplinary Science Research Council (SRC), and entered an era of competition with other sciences, and within astronomy with newly vigorous university astronomy departments such as the University of Sussex's near Herstmonceux. RGO's historical investment in and continuing dependence on optical astronomy meant that its focus shifted to international collaborations in Australia and the Canary Islands. This combination of external pressures and internal specialisation, combined with the erosion of its time-finding responsibility, made it vulnerable when funding pressures forced retrenchment and consolidation of government-funded astronomical research.

Final time

Despite these pressures, RGO's Time Department, which moved from Abinger to Herstmonceux in the mid-1950s, continued its leading role in the measurement of atomic time until the 1970s. Financial pressures increased and funding reduced, however, and SRC's successor, the Science and Engineering Research Council, finally withdrew its funding for the Time Department in the mid-1980s. The remnant of the Department was absorbed into the Nautical Almanac Office, still under RGO, but its residual involvement in time determination wound down in the later 1980s, and ceased in 1990 when, on its move from Herstmonceux to Cambridge, RGO's Time Service finally closed. Responsibility for the Pips went to the BBC, using Global Positioning Satellite receivers at Broadcasting House, whose signal was controlled by atomic clocks at the USNO in Washington. Thus, three centuries on from its foundation in 1675, the Royal Observatory finally lost its historic responsibility of providing time to the world. RGO itself did not long survive the loss.

The splitting of the post of Astronomer Royal from the Directorship of the RGO in 1971, compounded by the troubled tenure of the latter by Margaret Burbidge, severed an important linkage. New funding pressure in the 1980s forced the closure of Herstmonceux and the move to Cambridge. Thus when consolidation of publicly funded astronomy was forced in 1998, the diversified Royal Observatory Edinburgh survived when RGO did not [5].

Science does not, any more than time, stand still. In the post-war period the precision of time measurement improved at roughly 1 order of magnitude per decade. By 2015 it was accurate to 1 second in 300 000 000 years. Current research focuses on transitions at an optical wavelength, which offer better stability and finer resolution, with the possibility of future redefinition of time standards away from dependence on caesium clocks towards new technologies such as trapped ion optical clocks, and even more fundamental standards, such as the Rydberg constant that governs the structure of atomic spectra. This work happens at Teddington, the physicists now firmly and exclusively occupying the time-finding role that was for so long the responsibility of the astronomers at Greenwich.

Acknowledgement

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Interview: Carolyn Kennett Chair of the SHA



Carolyn, it is great having you as our new Chair and I hope you are enjoying it. How are you presently engaged in the area of astronomy?

At the recent October 2023 AGM, I was honoured to be elected as the Chair of the Society for the History of Astronomy. I'm passionate about continuing the society's impactful work and expanding our reach to new audiences. Alongside this, I serve as the director of a creative engagement company where we develop projects themed around astronomy, dark skies, and archaeoastronomy. Additionally, I teach GCSE astronomy at a local school.

What is your earliest astronomical memory?

I've always held a fascination for the sky, making it hard to pick just one memory. However, I distinctly recall sitting on my bedroom window sill as a child, gazing at the stars, planets, and the moon, attempting to discern constellation shapes.

What are your current interests in astronomy?

My focus lies in astronomical history within the

southwestern region of Britain. I currently act as the SHA survey contact for Cornwall and Dorset. I'm deeply intrigued by how ancient cultures might have interpreted the skies, and I'm finalising a book on stone circles enriched with archaeoastronomy. Collaborating with Dr. Peter Morris, I'm also co-authoring a book on eighty heavenly objects. Additionally, historical photography techniques captivate me, and I'm learning wet plate photography to capture a solar eclipse image just like they were taken in the 19th century.

Which astronomers (past or present) would you choose as companions for an observatory observing session?

The opportunity to observe with Caroline Herschel would be truly extraordinary. I'd also relish spending a day with George Biddell Airy during his Dolcoath Mine Experiments in Cornwall, witnessing the experiments first-hand deep within the mine. I reran a version of this experiment recently and realised how much we still had to learn about how they achieved the results they did.

And what music (if any) would you have playing in the background?

Perhaps something soulful, possibly by Gabriels, to complement the stargazing experience.

If you were only allowed one astronomy book on your bookshelf, what would it be?

It would have to be "Collins Stars and Planets" — a well-worn resource that sees constant use.

And if you had the chance to spend a day at any place of astronomical interest, where would it be?

Spending a day on the Moon would be an incredibly surreal and captivating experience.

Finally, what is your favourite astronomical phrase, motto or quotation?

"I'm sure the universe is full of intelligent life. It's just been too intelligent to come here" (Arthur C. Clarke).

The Venus Tablet of Ammisaduqa

Bruce Vickery *re-analyses the ancient clay tablet.*

The Venus Tablet of Ammisaduqa, (Figure 1), is a clay tablet containing Cuneiform writing. It was discovered in the 1850s in a dig in Babylon which unearthed a “library” of over 20 000 tablets.

Due to a sacking that had taken place around 600 BC all these tablets were in a poor state as can be gleaned from the image. Fortunately, however, this particular tablet is one of a number of copies that were created and virtually all of the content of the tablet has been reconstructed from this and other fragments found elsewhere.

The tablet contains 21 years’ worth of observations of the setting and rising of Venus and, due to containing a piece of text referring to “The year of the Golden Throne” it is known to have been created during the reign of King Ammisaduqa. In view of this there have been, over the past 100 years, many attempts to date the very specific observations of Venus using modern Solar System positional algorithms.

Archaeologists cannot pin down the exact date of the tablet from their extensive reading of other sources but by comparing possible solutions from the astronomical investigations, three possible pairs of dates have been identified as the most probable “first” date entry on the tablet. These date ranges are:

Low Chronology	1581 BC or 1589 BC
Middle Chronology	1637 BC or 1645 BC
High Chronology	1701 BC or 1709 BC

The reason that dates appear in pairs is that there is a “resonance” between the orbits of Venus and the Earth in that 8 Earth orbits and 13 Venus orbits are almost identical in length. So if a possible solution for the date is found there can be another potential solution 8 years away from it. Similarly there are 56 and 64 year resonances.

This is an added complexity to extracting a “unique” solution to the problem.



Figure 1: The Venus Tablet of Ammisaduqa, on display in the British Museum, London. (Wikimedia Commons.)

In order to ameliorate the problem of “repeat” solutions this study limited itself to searching the solution space over a 200 year period from 1550 BC to 1750 BC, which covers the three chronologies of interest.

Explanation of the Calendar

In order to understand the times of the tablet observations it is necessary to study the calendar in which they are recorded.

The Babylonians were using a fully Lunar Calendar containing 12 months called Nisan, Ayar, Simanu, Dumuzi, Abu, Ululu, Tashritu, Arahsamu, Kislimu, Tebetu, Shabatu and Adar, though it should be noted that some sources spell these months differently.

The first day of each month was when the first crescent of the Moon after New Moon was sighted, when it was almost invisible in the glare of the Sun. As the Synodic Period of the Moon is approximately 29.53 days, on average the 12 months are 354.4 days in total. So, 12 Lunar Months fall short of the full year that the Earth takes to orbit the Sun. Hence if no further adjustment is made to this calendar the months will move through the year and not be properly associated with any particular season. The Babylonians knew of this phenomenon and compensated for it by sometimes adding an extra month into the year. This extra month is called an “intercalary” month, and the Babylonians always added this month, when required, after the sixth month, Ululu, or the twelfth month, Adar.

The solution to this problem lies in part in the ability to create an accurate Babylonian Calendar using modern up-to-date astronomical algorithms.

Content of the Tablet

Table 1 shows the translated content of the stone. The column explanations are as follows:

The first column is the numerical listing of the pairs of observations.

The second column gives the year of Ammisaduqa’s reign for each of the pairs.

The third is the month of the year in which the setting observation was made, followed by its name in the fourth column and the day of that month in the fifth.

The sixth, seventh and eighth columns contain the observation for the rising.

Finally the right hand column contains the length of time that Venus was invisible at this particular conjunction.

In order to “solve” the problem, what is now necessary is to identify this pattern of the Moon which determines the years and months (i.e. the “calendar”) and the pattern of Venus for which the dates are given in that lunar calendar.

Astronomical Algorithms

It goes without saying that in order to solve this problem extremely accurate positions of the Sun, Moon and Venus with respect to the Earth must be available for the analysis to take place.

Such accurate algorithms are available in the public domain and an excellent book on this subject is one called *Astronomical Algorithms*, written by Jean Meeus [1].

It is claimed that Venus can be positioned to within 1 arcsecond using these algorithms, and that the Moon can be placed to around 10 arcseconds of accuracy. The author has built these algorithms into a software suite for representing the heavens for dates that include the ones required for this study. But more software than the basic suite is required. In order to create a Babylonian calendar the dates and times of the sighting of the first crescent Moon after New Moon must be acquired.

Sighting the First Crescent

One modern algorithm deemed particularly appropriate for predicting the sighting of the first lunar crescent is the “Yallop Algorithm” [2]. It is available online [3].

#	Year	Month Invis	Name	Day Invis	Month Vis	Name	Day Vis	Days Invis
0	1	XI	Shabatu	15	XI	Shabatu	18	3
1	2	VIII	Arahsamu	11	X	Tebet	19	2m 7d
2	3	VI	Ululu	23	VII	Tashritu	13	20
3	4	IV	Dumuzi	2	VI	Ululu	3	2m 1d
4	5	II	Ayar	2	II	Ayar	18	15
5	5	IX	Kislimu	12	XI	Shabatu	16	2m 4d
6	6	VIII	Arahsamu	28	IX	Kislimu	1	3
7	7	V	Abu	21	VIII	Arahsamu	2	2m 11d
8	8	IV	Dumuzi	25	V	Abu	2	7
9	8-9	XII	Adar	25	III	Simanu	2	2m 7d
10	9	XII	Adar	11	XII	Adar	15	4
11	10	VIII	Arahsamu	10	X	Tebet	16	2m 6d
12	11	VI	Ululu	26	VI(2)	Ululu2	7	11
13	12	I	Nisan	9	VI	Ululu	25	5m 16d
14	13	II	Ayar	5	II	Ayar	12	7
15	13	IX	Kislimu	20	XI	Shabatu	21	2m
16	14	VII	Tashritu	10	VIII	Arahsamu	26	1m 16d
17	15	V	Abu	20	VIII	Arahsamu	5	2m 15d
18	16	IV	Dumuzi	5	IV	Dumuzi	20	15
19	16-17	XII	Adar	25	III	Simanu	2	3m 9d
20	17	XII	Adar	11	XII	Adar	15	4
21	18	0	0	0	0	0	0	0
22	19	VI(2)	Ululu2	1	VI(2)	Ululu2	17	15
23	20	III	Simanu	25	VI	Ululu	24	2m 6d
24	21	I	Nisan	27	II	Ayar	3	7
25	21	X	Tebet	28	XII	Adar	28	2m

Table 1: The translated content of the tablet

This algorithm was programmed specifically for the present study and applied in full to create a Babylonian calendar between the dates of 1550 BC and 1750 BC.

From a calibration against NASA tables on their website [4], the algorithms are expected to be exact to the day 90% of the time and no more than 1 day incorrect for the other 10%.

As the “seeing” in Babylon cannot be recovered, an error of 1 day is of no real significance in seeking the solution of the Venus Tablet of Ammisaduqa.

Sighting of Venus

Venus disappears into the glare of the Sun at times when it is near or at both inferior and superior conjunction.

There is a question of how many days it remains invisible, and this is usually calculated by selecting an angle between the centre of Venus and the Sun’s centre and calculating the day on which Venus sinks below this angle (setting), and on which Venus ascends above this angle (rising). Typically this angle is around 6 degrees, and after experimentation, 6 degrees was used in this study.

Analysis

Once there is a calendar, and a sequence of the setting and rising of Venus in place, the comparisons with the Tablet contents can be performed.

A Least Squares process was employed by comparing each calculated data point with that on the Tablet, and adding the square of the difference to the Least Squares total.

All Superior Conjunction data points were left out of this analysis. As Venus approaches and departs the Sun very slowly at Superior Conjunction there are many days on which it is at an angle that could easily be affected by seeing and this makes their specific values very untrustworthy. Some researchers have estimated that the observations can be as much as 6 days incorrect. On the other hand, such an error is impossible for an Inferior Conjunction with only 3 days of the absence of Venus from the sky. This latter requires the Conjunction to have occurred within that 3 day period.

Result

The result of the Least Squares analysis is that 1645 BC is the best fit for the first observation pair on the Tablet. Even when calculations were made at different rising and setting angles for Venus 1645 BC came out on top.

“Problem” Observations

The foregoing discussion implies that the observations on the Tablet are “perfect” and therefore eminently amenable to the analysis that reveals the date of 1645 BC.

There are, however, some “bad” observations, some of which are being attributed to “scribal errors” in the copying of the original Tablet – which has never been found.

But the observations of years 12 and 14 stand out. Even someone new to the problem will see just how “out of line” these pairs of observations are.

In the case of year 12, Venus is invisible for over five and a half months. Calculations show that it must have set and risen at a higher angle from the Sun than is normal. Such could be attributable to an atmosphere that contains abnormal levels of aerosols—such as could be attributed to volcanic activity, or to a meteor strike.

Year 14 is a bit more complex. Venus sets—in the west—about 6 weeks early, but rises—in the east—at the correct time. Atmospheric pollution, if in play, would be in the west, and not homogeneous as it was in year 12.

Volcanic Activity

The “bad” pairs of observations can both be explained as the result of volcanic activity. Those studying such activity do have such in place at dates very close to those of the Venus Tablet.

The best modern paper on this subject is that of McAneney and Baillie [5]. Application of their work to the observations tells us that the observations for year 12 are probably due to a volcano in Alaska called Aniakchak and those of year 14 could be due to the explosion of Santorini in the Mediterranean which is to the west of Babylon.

Summary

Why has this Tablet, of all tablets, survived for so long? It is the opinion of the author that the answer to this lies in the two volcanoes mentioned in the above section. The Babylonians would have been puzzled by the early setting and late rising that they observed and decided to record and copy this Tablet to protect the observations so that these strange behaviours could be explained in the future.

That future has now arrived.

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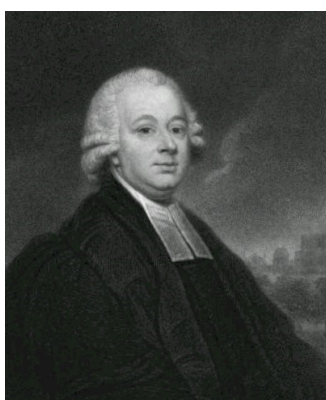
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Figure 1:
Nevil
Maskelyne,
Astronomer
Royal 1765–
1811.
(Wikimedia
Commons.)



Celebrating... The 250th anniversary of the Schiehallion Experiment

In 1774, an intrepid team, led by the Astronomer Royal Nevil Maskelyne (Figure 1) set out to undertake a bold set of experiments that would determine the density of the Earth.

The destination and target was the mountain Schiehallion, in Perthshire, Scotland (Figure 2) and the aim of the expedition was to determine the mean density of the Earth. A similar attempt had been made decades earlier by Bouguer and de la Condamine but was unsuccessful owing to the harsh conditions in South America. The basis of the experiment was the measurement of the tiny deflection of a pendulum hanging next to the mountain, the gravitational attraction yielding information about the mountain's mass. Schiehallion, too, presented problems, but in 1775, in his paper to the Royal Society, Maskelyne declared that he and his colleagues had measured a deflection of 11.6 arcseconds, which put the mean density of the Earth at 4500 kg m^{-3} .

Modern measurements differ from this by only by about 20% but the experiment was perhaps more valued because of the support it gave to Newton's theory of gravity.

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Figure 2: the mountain Schiehallion, site and subject of the famous experiment. (Wikimedia Commons.)

Mad Jack's Observatory at Brightling

In the first of two parts, Philip Taylor describes a remarkable building tucked away in East Sussex.

The northern parts of East Sussex still contain quiet and unspoilt countryside within the High Weald Area of Outstanding Natural Beauty. A visitor travelling along the narrow lanes west of Robertsbridge will be intrigued to see a number of unusual structures dotted around the countryside near the village of Brightling. These include an obelisk (the Needle), a small conical building known as the Sugar Loaf and the round stone Tower. There is also a Temple built in the classical style as well as a Summerhouse, both typical features of the landscaped park surrounding the main house at Brightling Park, close to the centre of the village of Brightling. The local churchyard features an unusual tomb in the form of a pyramid. One of the most prominent of the structures is the domed building on the highest point in the area, now a private residence known as The Observatory.

These structures, usually considered to be follies, were built by John Fuller (1757–1834) [Figure 1] the local squire and owner of the Brightling estate (previously known as Rose Hill). He was the local squire, a politician, philanthropist, patron of the arts and science and a slave-owner. He is popularly known as “Mad Jack” Fuller on account of his eccentricities including the building of many follies, although he himself wanted to be known as “Honest John” Fuller. The purpose and history of Fuller’s follies have been the subject of speculation, myths and legends over the years, with hard facts difficult to pin down. This is as true for the Observatory as for the other buildings, with few contemporary records surviving and even those that do exist being of doubtful accuracy.

The two high points on Brightling Down, to the west of the village, both reach an altitude of 195 metres (640 feet) with the Brightling Needle on the northern summit and Brightling Observatory directly to the south. This article will describe what is known about the Observatory, which is sometimes regarded as one of Fuller’s follies but which was originally described as a building intended for scientific research, equipped with advanced astronomical equipment.



Figure 1: Engraving of portrait of Jack Fuller. Original oil painting by Henry Singleton. (National Portrait Gallery, London.)

John Fuller

John (“Mad Jack”) Fuller (1757–1834) was a colourful figure, a man of many parts, who is now remembered mainly for the construction of the many follies still visible near Brightling. The first full-length biography of Fuller was published recently, written by Annette Lloyd Thomas [1].

In 1777 at the age of 20, Fuller inherited the Rosehill estate in Sussex and Jamaican plantations (including 290 enslaved people) from his uncle Rose Fuller MP. In 1780 Jack Fuller was elected to the House of Commons. He was the Tory Member of Parliament for Southampton from 1780 to 1784, and for the county of Sussex from 1801 to 1812. In Parliament, Fuller was a member of the “West India lobby”, a group of plantation owners and their supporters in the British Parliament who fought against the abolition of slavery. Fuller was outspoken in his defence of slavery.

Fuller gained a reputation for heavy drinking and this probably led to the well-publicised incident on 27 February 1810 when he was rebuked by the Speaker of the House of Commons. He was then seized by the Serjeant-at-Arms and imprisoned for 3 days. Hansard records that he *“misbehaved himself during the sitting of the Committee, making use of profane oaths, and disturbing their proceedings, John Fuller esq. member for Sussex, the member complained of, was heard to excuse himself; in the doing of which he gave greater offence, by repeating and persisting in his disorderly conduct”*. [2] When he was released, Fuller was brought before the House and reprimanded after another MP described how *“he had sat for 20 years in the House and never witnessed such a gross outrage as had been committed the other night”*. [3]

Fuller took a keen interest in both arts and science, including astronomy. Although not present at the first meeting of the Astronomical Society of London in 1820 (which became the Royal Astronomical Society in 1831), he is listed as one of 83 members of the Society prior to its first meeting [4]. He was one of the 8 early members of the Society who owned a private observatory [15]. By June 1822, Fuller was one of the 200 men who had been proposed as Fellows of the Society. Unusually, Fuller was listed

twice: as number 59 (presumably not elected) as well as number 174 [5].

Fuller probably had personal acquaintance with two of the original Secretaries of the Astronomical Society of London. Fuller’s London residence was at 36 Devonshire Place and during the 1820’s Fuller lived close to both Charles Babbage at 5 Devonshire Street (resident 1815–1827) and John Herschel at 56 Devonshire Street (resident 1824–1832).

Inception of the Observatory

Brightling Windmill was formerly situated on one of the high points of Brightling Down with extensive views to Sussex and Surrey hilltops as well as Beachy Head near Eastbourne. The location had been identified in the 18th Century as an important viewpoint by those carrying out early geodetic surveys. Observations had been made at Brightling in 1787 by William Roy when determining the difference in longitude between the meridians of Greenwich and Paris. [6]. Subsequently the location was used during the first high-precision triangulation survey of Great Britain, beginning in 1791. The second “great theodolite” built by Ramsden was used for this survey and in 1793 a series of observations were made from Brightling, the instrument having been set up in the field adjoining the windmill [7].

Fuller left the House of Commons in October 1812 which gave him more time to devote to his scientific and artistic interests. Perhaps inspired by those previous visits by surveyors, sometime about 1812 the windmill was demolished to make way for an astronomical observatory. The first public mention of Fuller’s new observatory was in the Sussex Advertiser newspaper published in Lewes on 3 August 1812.

Shortly afterwards, this news item was reproduced along with a satirical commentary in the Belfast Commercial Chronicle on 12 August 1812. The author clearly did not take the announcement very seriously and alludes to Fuller’s oratory in the House of Commons as well as his drinking habits, suggesting that the observatory might have a “well stowed cellar” allowing Fuller to “see double”:

"The astronomical world, we are assured will read, with great pleasure the following paragraph which we copy verbatim from the Lewes Paper as inducing a hope that the scientific exertions of Mr Fuller, during the recess, may be productive of discoveries calculated to raise his name ad astra: John Fuller, Esq one of our county members is erecting an Observatory, on that delightful and commanding eminence, whereon a windmill lately stood on Brightling Down and to give better effect to his astronomical pursuits. Mr. Fuller has purchased that famous telescope, which the late Sir George Shuckborough so much prized for its excellence, being the best ever manufactured in England ... This gentleman the thunder of whose eloquence has frequently shaken the walls of St Stephen's Chapel, and called forth more shouts of hear! hear! that ever followed the financial demonstration of Pitt - the impassioned eloquence of Fox - the florid oratory of Burke - or the keen and polished wit of Sheridan - may sit, and nightly spell, Of ev'ry star the sky doth shew' and, perhaps, with the aid of his favourite telescope, he may detect some hitherto unobserved luminary ... The writer of this paragraph which we have just quoted has not informed us whether a well stowed cellar, and a plentiful larder are attached to the observatory. We sincerely hope that they are; as in that case, Mr. Fuller will be enabled nightly to see double—and his discoveries will of course, increase in the same ratio ... Blush! Blush! ye depraved senators who are at this moment either sunk in ignoble ease - or, if employed, employed in the mean sports of the country - turn your eyes to Brightling Down and let the example of 'honest Jack Fuller' claim ye from folly.*

***Mr. Fuller's voice is of the Stentorian order."**

Further embarrassment for Fuller came a few days later with this statement, originally published in the Sussex Advertiser, reprinted in the Globe newspaper of 13 August 1812:

"When we in our last mentioned that Mr. Fuller had purchased the late Sir George Shuckburgh's telescope, we certainly did not mean his great equatorial, which we understand has been lately presented, by Mr Jenkinson, to the Royal Observatory at Greenwich, where preparations are making for fixing that valuable instrument, which is said to be the first in Europe of its kind.

The Observatory which Mr Fuller is erecting in the neighbourhood of his house, at Rosehill, is to be put under the management of a very able Astronomer; and, for the purposes of comparison, at least, we are persuaded, it will be found very useful. Mr Fuller, we understand, is about to endow a Charity School, at Brightling"

The statement about the Shuckburgh telescope clearly contradicts the original announcement which mentioned "that famous telescope" formerly owned by Shuckburgh, "much prized for its excellence", which was an obvious reference to the "Great Equatorial". In fact, no other telescopes were disposed of from Shuckburgh's estate.

The "very able Astronomer" and a new school are mentioned again in the observatory description published in 1813, discussed below.

The Shuckburgh telescope [Figure 2], as described in the Antiquarian Astronomer article by Peter Hingley [8], was a five-foot telescope of 4.2 inch aperture, completed by Ramsden in 1791 and was



Figure 2: The Shuckburgh Equatorial. Drawn by J Farey Junior and engraved by Sidney Hall, the plate is a re-drawing of the original published in Philosophical Transactions in 1793. From Rees's Cyclopaedia (London, 1820). (Information from Graham Dolan.)

notable as being the world's first large equatorially mounted telescope. Sir George Shuckburgh died in 1804 and the telescope was donated to the Royal Greenwich Observatory in 1811 by his heir the Hon. Cecil Jenkinson. The claim that it was the "best ever made in England" was later disputed and it was said to have many deficiencies, as described by Pearson in 1829 [9]. Fuller was obviously interested in the Shuckburgh telescope and had hopes of acquiring it. It had been offered to the Radcliffe Observatory in Oxford who declined it [10] but was accepted by Greenwich, where it finally arrived in August 1812 [11], the very same month as the newspaper announcements about Fuller's new observatory. It seems that Fuller had missed his chance of obtaining this well-known telescope, hence the newspaper retraction.

Observatory Design by Smirke

The most important contemporary document regarding the Observatory is the architectural drawing [Figure 3] by Sir Robert Smirke, now in the archives of the Royal Institute of British Architects (RIBA) and located in the V&A Library (RIBA Ref. 67562).

Sir Robert Smirke (1780–1867) was a British archi-

tect who was an important figure in Greek Revival architecture. He designed many public buildings, including the British Museum for which he is now particularly remembered. Many of his early commissions and his rapid rise to prominence were due to his political connections—he was a Tory party supporter, as were many of his patrons, including Fuller.

Smirke's Observatory design is thought to date from 1807. The single sheet is titled "*Preliminary design for an observatory, Brightling Park (formerly Rose Hill), Brightling, Sussex, for 'Mad Jack' Fuller: floor plans, sections and details of machinery*". It illustrates various aspects of the proposed observatory, including additional drawings showing details of astronomical equipment. The main plan view shows a building with a portico entrance leading to a central area at the base of a dome (marked "Rotatable"). On each side, there are two further rooms: on the left, rooms marked "Mural-circle Room" and "Transit Room", containing representations of mural-circle and transit telescopes. The sketch of a "mural circle" does not actually represent such an instrument, which should be attached to a wall. On the right, there are further rooms marked "Lecture Room" and "Study".

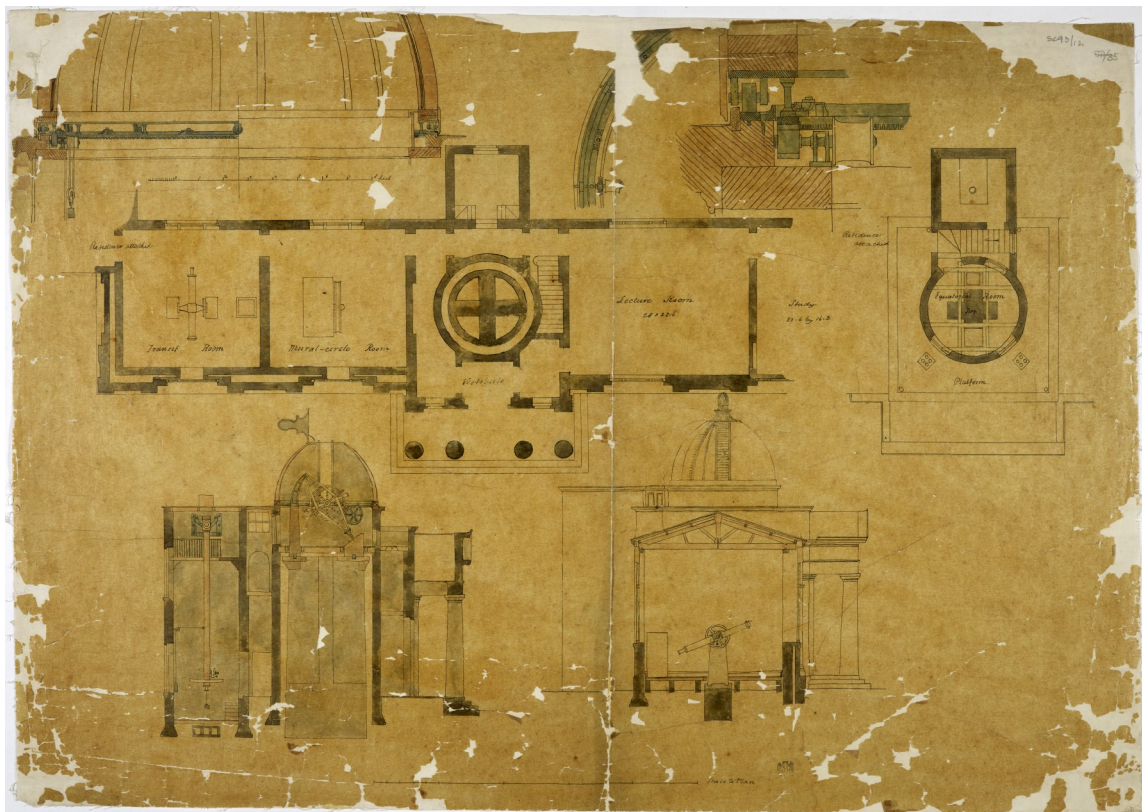


Figure 3: Smirke's design for Brightling Observatory. (Royal Institute of British Architects. Reference RIBA 67562.)

The additional drawings include the following:

At the top of the drawing (now damaged), are 2 diagrams showing the dome mounting and a close-up of its rotation mechanism.

Centre Right. A plan view of the upper-storey circular "Equatorial Room", adjoining this a smaller room with a single small circle (tube) in the centre.

Lower Left An elevation view of the central dome showing a tall central pier supporting an equatorially mounted telescope. The telescope is shown with an English style mount which bears a clear resemblance to illustrations of the Shuckburgh equatorial [Figure 4].

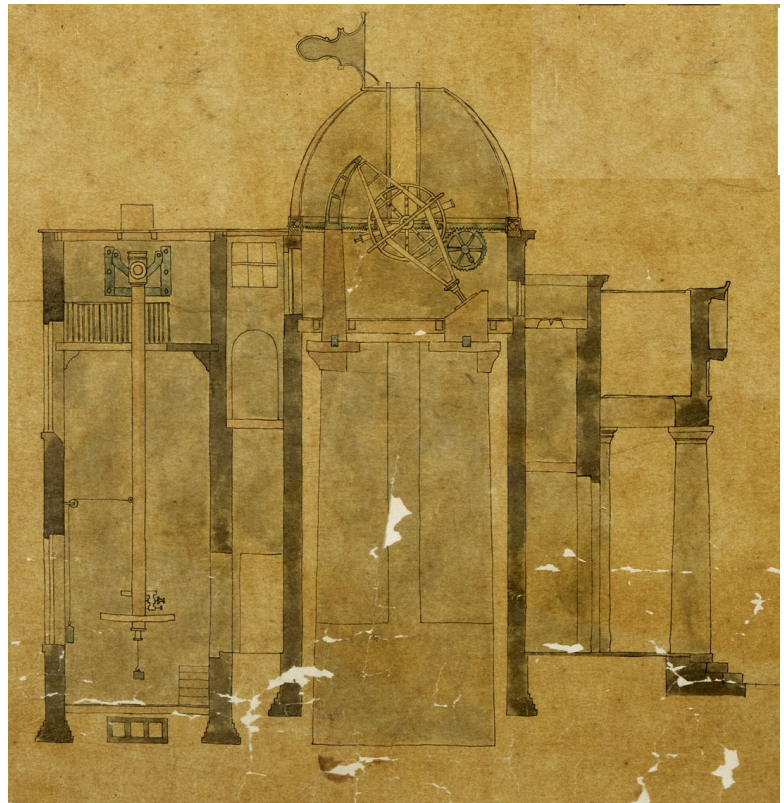


Figure 4: Telescope in Smirke's Design. Detail from Smirke's plan as shown in Figure 3.

To the left of the dome, a tall, narrow room is shown containing a thin vertical telescope tube with a micrometer and eyepiece at the bottom and pivoted supports at the top. A wire attached to the tube is linked via a pulley to the wall with weight suspended below. A free hanging weight (plumb-line) is shown suspended below the eyepiece. This instrument appears to be a Zenith Tube telescope, similar to that installed in 1812 by Pond at Greenwich.

At the top, a pivoted cupola on top of the dome is shown in an open position above the dome slit.

Lower Right. An elevation view of the Transit Room with the central dome behind it, showing a transit telescope resting on a below-floor solid pier with a shuttered window on each side.

In summary, the design by Smirke proposes an ambitious astronomical observatory built in the classical style, containing a large equatorially mounted telescope as well as equipment for positional astronomy including Mural Circle and Transit telescopes as well as a Zenith Tube. To make effective use of this equipment would have required at least one dedicated astronomer working on-site with a

long-term, systematic observing plan.

The building as it now stands has an unusual shape and consists of two sections, perhaps built at different times:

A T-shaped observatory which is a smaller version of the building in the Smirke design. It has an entrance hall with a staircase leading up first to the first-floor level providing panoramic views where further steps lead up to a domed observing floor. There is just one, instead of two rooms, on each side of the entrance hall. The Transit room (now the drawing room) behind the entrance hall still retains full-height shutters on both the North and South sides. The external shutters still exist but are now partially blocked by interior plasterwork.

A semi-circular extension at the front, forming an open courtyard area in front of the original entrance. This area provides four further rooms (now bedrooms and kitchen) alongside a new front entrance. Comparison of the stonework suggests that this part of the building may have been added to

this part of the building may have been added to the original observatory to make it suitable for residential use.

1816 Inventory

A brief list of the Observatory's contents was made in April 1816 and is preserved in the East Sussex county archives [12]. It is not known why the inventory was produced at this time or who, if anyone, was occupying the building. The document is headed "*Household Furniture belonging to John Fuller Esq at the Observatory*" and lists the contents of eleven rooms, confirming that the rooms in the front extension had already been built by that time. The contents include an assortment of furniture and the building seems more domestic than scientific, including bedrooms, kitchen, dairy and wash-room. The Transit Room is described as containing a "Time Piece", an astronomer's chair and "Spirit Level and Instruments". The timepiece was probably the transit clock mentioned in 1813, but there is no information about what the instruments were. It did indeed have a cellar, which is listed as containing two barrels, perhaps of beer.

Observatory description, 1813

The publication *The Monthly Magazine or British Register* for September 1813 contains an article entitled *The Present State of Astronomical Observatories in the British Islands &c.* [13]. It is dated July 5th with the author identified only by the initial "K". A list of 21 private observatories is provided, including that of Fuller at "Rose-hill, Sussex". The list is almost identical to that provided (probably in the same year) in Rees's *Cyclopaedia* [14] and subsequently in Hutton's *Dictionary* of 1815 [15]. The Rees's *Cyclopaedia* entry has been attributed to William Pearson [16]. A lengthy footnote to the 1813 *Monthly Magazine* article provides a description of Fuller's observatory which, apart from the brief and unreliable 1812 newspaper reports, appears to be the only contemporary account:

Mr. Fuller has lately appointed a gentleman to be his astronomer, with a liberal salary, who was instructed by Mr. Firminger, assistant astronomer at the Royal Observatory at Greenwich, from the year 1798 to 1807; and to render the observatory useful, he has

connected the office of astronomer with the director of a school Mr. Fuller has lately established for the dissemination of learning in that part of the country.

The observatory erected by Mr. Fuller, of Rose-hill, is a beautiful building, executed by Smirke; it contains a transit room for meridian observations; an equatorial moveable roof in the shape of a hemispherical dome, covers a fine pillar of stone which runs up through the middle of the building, and is destined to support one of the best repeating circles Mr. Troughton ever made, which was lately in the possession of Mr. Pond. The great value of such an instrument can only be estimated by such astronomers as are conversant with the exquisite nicety required in making the modern astronomical observations.

Beneath this beautiful dome is a large room for the use of a telescope, for making observations of the eclipses of Jupiter's satellites, occultations of stars by the moon, &c. The instruments already provided are a transit instrument and transit clock, a fine five-foot achromatic telescope, by Dollond, which cost one hundred and eighty guineas, mounted on equatorial stand, and furnished with every apparatus necessary for rendering it one of the most useful instruments of practical astronomy.

The repeating circle above mentioned, will be a valuable instrument for observing zenith distances, for which purpose perhaps few instruments are superior, except when made on a scale like the Greenwich mural circle. A theodolite has also been lately made by Jones, of Oxendon-street, which has the advantage of having been divided upon Mr. Troughton's new method, and which in other respects is considered a masterly piece of workmanship.

This footnote provides many details about the observatory and its equipment. Unfortunately, as is often the case with Fuller's projects, some of the information may not be reliable.

[The article will continue with Part 2 in Bulletin 43.]

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Catching up with the past

Ah – I see you are reading Brecht's *Life of Galileo*. Are you enjoying it?



Hello? Are you ok?



(I must be silent from the highest of motives...)



Revealing the world of galaxies, one hundred years on

Marking the centenary of Edwin Hubble's great discovery, astrophysicist and galaxy researcher Jean-René Roy discusses details of how the revelations emerged.

In 1924, American astronomer Edwin Powell Hubble established the distance of the “Great Nebula” in the constellation Andromeda, clearly placing it well outside the limits of our Milky Way. All of a sudden, the observable universe had just expanded by at least a million times.

On fine evenings of late summer and autumn, you can observe in the constellation of Andromeda what appears through binoculars as a small diffuse object. From a location free of light pollution, you can even see this strange object with the naked eye. The ancients had noted it (Figure 1). In his magnificent *Book of Fixed Stars* published in 964, Persian astronomer Abd al-Rahman al-Sūfī (903–986) of Isfahan identified the puzzling object as the *Little Cloud* [1]. In 1612, German mathematician Simon (Mayer) Marius (1573–1625) became the first to observe the ‘nebula’ using a *perspicillum belgicum*, or telescope on 15 December 1612; he described it as “the light of a candle shining through a horn and seen from a distance” [2]. The *Little Cloud* is well known today: it is the Andromeda Galaxy.

With the advent of the telescope, other foamy-like clouds were discovered. French astronomer Charles Messier (1730–1817) was a comet hunter. He had listed the *Little Cloud* in his catalogue of nebulae with the number 31 [3]. Messier warned that if one was looking for new comets, Messier 31 was not to be confused with one. At 2.5 million light years, it is the most distant object that can be seen with the naked eye. A little disappointing seen in a small telescope, one should remember that the light that reaches our eyes today was emitted by the stars of the Andromeda Galaxy while our hominin



Figure 1: Andromeda and Pisces constellations as shown by Al-Sufi in *The Book of Fixed Stars*. The *Little Cloud* is shown as a little dotted box to the right of the fish mouth. Credit: Universität Erfurt.

ancestor *Homo habilis* roamed the savannah of South Africa.

Imagining galaxies – the prehistory

In the second half of the 18th century, the exploration of nebulae took a new life. Their study followed two parallel tracks: firstly, an empirical one, solidly

observational, taken by the German-born musician and astronomer William Herschel (1738-1822) and his astute sister Caroline (1750-1848); and secondly, a highly speculative avenue, roamed by three philosophical writers, Thomas Wright, Johann Heinrich Lambert and Immanuel Kant.

Being of cautious mind, William Herschel tried to make sense of the numerous nebulous objects scattered across most of the sky that Caroline was finding with her comet-sweeper telescope. As she noted, there were many more than Messier had listed in his catalogue. Like others, Herschel battled with the challenge of determining the nature of nebulae [4]. Some appeared to be resolved into stars and others not. Amidst lots of contradictory reports, a struggling Herschel made successive hypotheses: were nebulae simply clusters of unresolved stars? Could they be other Milky Ways viewed from great distances? Opting for safer ground, he came to favour nebular matter of an unknown nature, some shining fluid, spread amid stars. Later, influenced by ideas from Kant, he saw nebulae as solar systems in formation. Although he kept changing his mind regarding the nature of nebulae, Herschel did more than any other astronomer to trigger the transformation of our views of the large-scale cosmic world [5].

The mystery of nebulae had also captured the attention of 18th century philosophers. It was with an increased vigour, that eminent European thinkers undertook to describe the large-scale structure of the heavens and of its content. They employed a mix of theosophical and physical considerations, all highly speculative.

English astronomer and mathematician Thomas Wright of Durham (1711-1786) remains known chiefly for his moral cosmology book *A Theory of the Universe* (1750) [6]. In this work, he dealt with the various astronomical phenomena and sought a unified explanation. He subsequently tried to explain novae, variable stars, nebulae and comets and the Milky Way in terms of volcanoes in a solid celestial sphere [7]. The Franco-Swiss polymath Johann Heinrich Lambert (1728-77) was the second moral cosmologist captivated by nebulae. He elaborated a hierarchical system of clusters of stars spreading over across millions of light-years of si-

dereal space. However, Wright and Lambert's fancy speculations had little impact on the thinking of contemporary astronomers.

Nevertheless, Wright's ideas did influence the young German philosopher Immanuel Kant (1724-1804). Kant was less restrained by theological references and, fortunately, he wrote more clearly than Wright. He borrowed from Newton's theory of gravitation in explaining cosmic shapes and systems. In his youthful work *Universal Natural History and Theory of the Heavens* of 1755, Kant proposed that nebulae were systems of many stars, whose distance makes them appear as a uniform pale glow [8]. He also contributed to an idea incompatible with this initial proposal; that is, nebulae could also be planetary systems in formation. This cosmogony influenced Herschel's interpretation of some nebulae, those he called "planetary nebulae". We now know these planetary nebulae are envelopes of gaseous ejecta from red giant stars.

With this mix of speculative and contradictory hypotheses, such thinking had reached its limits. Let us move to the work of dedicated observers of the sky. Action happened first in an unusual location: mid-19th century Ireland.

On the road out of confusion

Irish gentleman astronomer William Parsons (1800-1867), the 3rd Earl of Rosse, was a dedicated politician and an impressive scientific polymath. Parsons' wife Countess Mary (1813-1885) possessed a solid financial endowment and was also competent technical help [9]. The Parsons set up an impressive observatory on their property at Birr Castle, Ireland [10]. The site was equipped with telescopes built following models based on mounts and metal mirrors developed by William Herschel. The Parsons had also added an impressive workshop for metal work, mirror production and polishing as well as for equipment maintenance. Several assistants were helping with the work and the observing.

The engineering and observing work conducted at Birr Castle was a research program in the modern sense: observationally, the programme consisted of a systematic search and examination of the nebulae and star clusters that had been found by William



Figure 2: The Whirlpool Galaxy, also called Messier 51. A portrait assembled from multiple sketches done at the Leviathan at Birr Castle (left), and the corresponding negative image in the V band by the Hubble Space Telescope (right). Situated at about 25 million light-years, it was the first spiral galaxy identified in 1845. In both images, dark and shading corresponds to stellar light, and whitish region to dust. Credit: The Sheridan Libraries, John Hopkins Library/NASA& ESA.

and Caroline Herschel [11]. As there was questioning about the reality of several of these objects, a first step of the observing programme was to confirm the existence of all catalogued objects. A few were declared not to exist; others to have been incorrectly located in the sky or to be duplicates in catalogues.

Beyond the clean-up and verification process, the Birr Castle observers paid meticulous attention to the description of the celestial objects and to their drawing. Parsons' initial motivation was to resolve 'nebulae' into stars with the new 72-inch aperture telescope; it was called "The Leviathan", originally the name of a sea monster but a word used for anything unusually large. Parsons' plan was soon derailed by the discovery of spiral structure in dozens of nebulae. The sequence of discovery unfolded quickly. Through the nights of April 1845, the studious Birr Castle observers made a portrait of a well-known nebula, Messier 51 in the constellation of Canes Venatici [12] (Figure 2). The power of The Leviathan allowed the discovery of the spiral structure of Messier 51 which became known as the Whirlpool Galaxy. Rapidly, several other nebulae were found to be of the spiral type, including

Messier 31, the object of our historical look-back. Spirality added another piece to the nebular puzzle. Speculation on the nature of nebulae amplified.

Parsons never gave a hint of any views he may have held regarding the nature of nebulae in his conferences or publications; his reporting remained strictly factual. One can however imagine the hours of discussion and speculations among the members of the close-knit team at the castle-observatory. These ubiquitous spirals: what were they? Unresolved groupings of stars? Some shining fluid or a mix of a mysterious fluid where stars were embedded, as the pioneering work of William Huggins (1824–1919) was indicating? Controversy and confusion about what nebulae were continued to rage for a few decades.

Paradoxically, as imaging techniques got more sensitive, telescopes got larger and better and astrophotography increased in use, confusion grew: more nebulae were shown or claimed to be resolved into stars, while most remain 'cloudy'. Proponents of the local hypothesis—that is nebulae are all parts of the Milky Way—argued that if nebulae were resolved into stars, they had to be relatively

nearby, that is, they were members of the Milky Way system. The controversy spilled well into the first two decades of the 20th century, as swings in opinion favoured alternatively the local hypothesis and the island universe model.

Resolving nebulae into stars became a battleground. Claims of resolution of some nebulae into individual stars were heard repeatedly. Both proponents and opponents of the extragalactic hypothesis employed the partly fallacious argument of resolution to support either the local or external version of the nature of nebulae. If nebulae were large systems of stars, we should see these. But, resolving the stars requires powerful telescopes, and furthermore, a stable atmosphere free of turbulence; bubbling air just smears stellar images—this is what is observed as the scintillation of starlight.

But why did so many claim to have resolved individual stars in nebulae? A possibility is that the optics of the telescope used, especially metallic mirrors, combined with atmospheric turbulence could have generated an apparent granularity in the image as viewed with the eyepieces of these instruments. Stated bluntly by Pulkovo Observatory director Otto Wilhelm Struve, “the alleged miracles of resolution were nothing but illusions.” Struve was right. While stars could indeed be observed associated with some nebulae, like that of Orion, most remained unresolvable into individual stars.

Topping the pile of nebular puzzles and visual illusions, some observers claimed to have detected variability of brightness in a few nebulae. Presumed changes in apparent brightness were used as a strong argument in favour of the local hypothesis. The argument, and it was a logical one, was that no giant systems of stars could cohesively vary in unison. The claims of variability were all erroneous. Hidden in the noise, German astronomer Julius Scheiner (1858–1913) bluntly summarized his spectroscopic Andromeda results in 1899: “No traces of nebular lines are present, so that the interstellar space in the Andromeda nebulae, just as in our stellar system, is not apparently occupied by gaseous matter”. [15]

Things were about to change swiftly in favour of the

‘island universe’ hypothesis of Kant. With significant technological advances, the second decade of the 20th century witnessed the spectacular rebirth of the hypothesis of the external nature of nebulae and the establishment of the world of galaxies [16].

Extragalactic ‘novae’

In 1917 the terrible World War I was raging. While European scientists were on the battlefield, in America, many of their colleagues away from the frontlines were pursuing their research. For astronomy, 1917 was a year of reckoning, when astronomers got a solid grasp of the idea that our Milky Way may indeed be one of numerous giant stellar systems, and that a multitude of similar “island-universes” or galaxies, still named nebulae, were scattered at colossal distances from each other. An end to endless speculation was in sight.

Key findings came from two lines of evidence: first, observations of extragalactic ‘novae’ and, second, measurements indicating that spirals were receding from the Milky Way at very high speed. The revealing discoveries were enabled by the new telescopes that American astrophysicist George Ellery Hale (1868–1938) had planned and built in the mountains of Southern California.

First, novae. These were the first type of extragalactic stars identified using photography. Using the new powerful 1.5-m reflector telescope at Mount Wilson Observatory in California, astronomer George Ritchey (1864–1945) was searching for variable stars in nebulae, stars whose brightness varies over a short period of time, a few days or weeks. Photographing nebulae, he found examples of a relatively rare type of explosive star: novae. Novae were well known and several had been observed in the Milky Way over the previous decades.

Today we know that nova brightening is triggered by the dumping of material from a red giant companion star onto a compact white dwarf, igniting a catastrophic nuclear detonation at the surface of the receiving star. A white dwarf is the dense and compact remnant of an evolved star and is about the size of the Earth. The rapid brightening lasts for a few weeks. Hence novae could be registered on

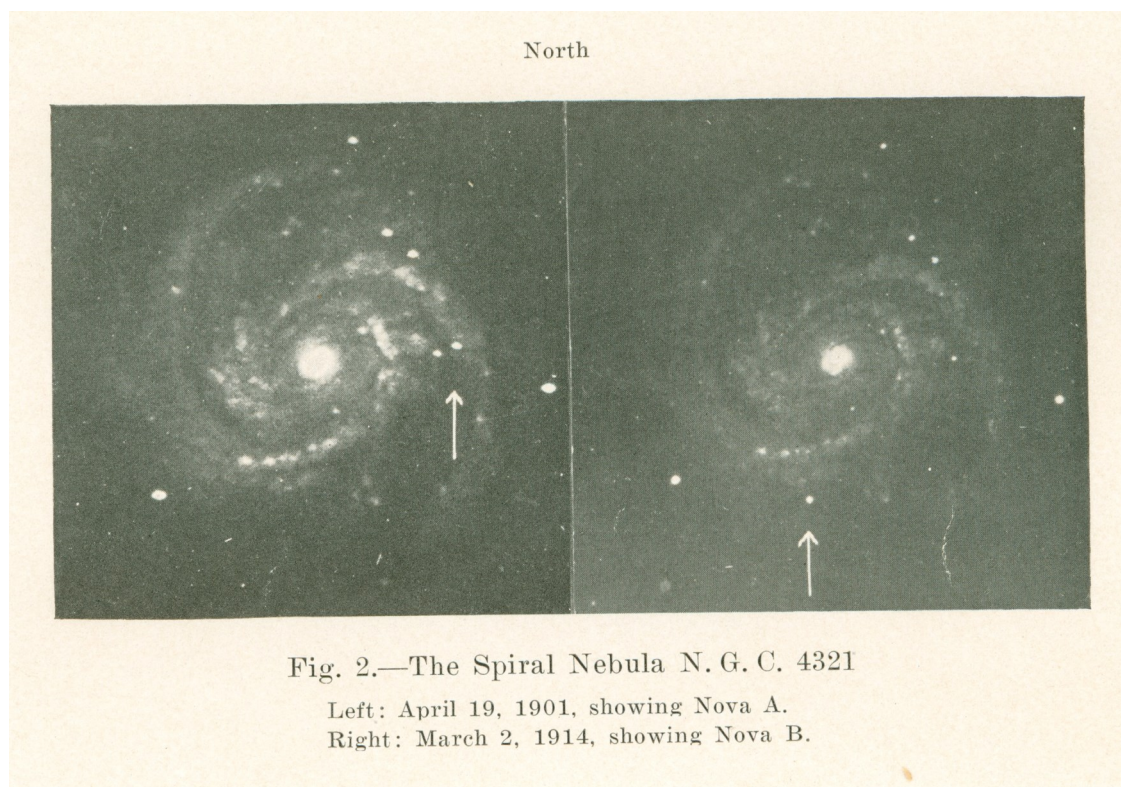


Figure 3: Supernovae (star like objects indicated with arrows) in the spiral galaxy NGC 4321 identified by comparing two images, one obtained in 1901 and the other in 1914. Credit: Lick Observatory Bulletins.

photographic plates taken only weeks apart. Although he did not then know the nova mechanism, Ritchey correctly declared novae to be as numerous in the Andromeda Nebula as they were in the Milky Way, that is about a dozen events a year. The objects appeared very faint, he explained, because of their much greater distances. He also found novae in a few other spiral nebulae. Ritchey assumed that they were analogues of novae in our own Milky Way. Scaling for their difference in brightness, they implied distances to the host systems to be millions of light-years! This put these spirals far beyond the Milky Way.

A bit farther north of California, the mountain site of Lick Observatory on Mount Hamilton also offered fine observing conditions. Astronomer Heber Curtis (1872–1942) had been conducting a systematic survey of the sky with a new wide field photographic camera installed on the Lick Crossley 0.9-m reflector. His purpose was to survey the sky for nebulae. The Crossley camera covered 0.9 degrees at once, a field of view almost 10 times that of the apparent size of the Moon. With only a few areas of the sky observed, the deep photographs revealed

thousands of spirals [17].

Like Ritchey, Curtis was also aware of novae in spiral galaxies and he found some in sky survey photographic plates. The procrastinating Ritchey did not immediately proceed with publishing his findings. Curtis did otherwise; rushing to the Crossley telescope photographic plate archive of spirals, Curtis found more novae. He quickly prepared and published his results before Ritchey managed to do so [18]. Like Ritchey, Curtis argued that the spirals were twenty million light-years away and sixty thousand light years in diameter.

The novae observed by Ritchey and Curtis were not all the same. Novae observed in the nearby Andromeda Nebula were novae similar to those observed in the Milky Way. Those in the other spirals were actually *supernovae*, much more powerful exploding stars (Figure 3). Walter Baade (1893–1960) and Fritz Zwicky (1898–1974) established their nature in 1934 [19]. However, Ritchey and Curtis's basic conclusion was correct: most nebulae are extra-galactic, external to the Milky Way. Unfortunately, novae light curves are irregular and



*Figure 4: Edwin Hubble examining a photographic plate.
Source: Science Collection at the Huntington Library.*

diverse, making them too unreliable to convince supporters of the local hypothesis that most nebulae resided far away, or even that they were the equivalent of Milky Way novae. But novae were paving the way.

Speeding 'nebulae'

Another independent direction of study led to distance determinations that also put most nebulae well outside the boundaries of the Milky Way. This work was based on spectroscopy, a transformative technique introduced during the first decades of the 19th century by German physicist and optician Joseph von Fraunhofer (1787–1826). Following Huggins' work, several spectrographs were installed on telescopes at the end of the 19th century.

In a paper also published in 1917, American astronomer Vesto Slipher (1875–1969) reported on the velocities he had derived from the spectroscopy of several nebulae using the Doppler effect. Slipher's observations were the results of a painstaking and relentless programme using the 60-cm refractor at Lowell Observatory, Arizona. Slipher was a patient

and meticulous observer, persistently piling up multiple nights of exposure to get twenty to forty hours of photons trickling on each photographic plate. From his spectroscopic plates, he derived the movements of several nebulae with respect to the Milky Way. What Slipher found was phenomenal.

A few objects like the Andromeda Nebula were moving towards us. However, the majority (17 out of 21) were receding at high velocities, in some cases reaching 1100 km per second. At such speeds, they could not be retained by the gravity of the Milky Way. Slipher wrote: "It has for a long time been suggested that the spiral nebulae are stellar systems seen at great distances. This is the so-called 'island universe' theory, which regards our stellar system and the Milky Way as a great spiral nebula that we see from within. This theory, it seems to me, gains favour in the present observations." [20]. The table was set for the next, and crucial step for positioning precisely extra-galactic nebulae in space.

Hubble cuts the Gordian knot

In 1924, Edwin Hubble (1889–1953) used the most accurate astronomical distance indicator to establish distances to "extra-galactic nebulae" with an unprecedented accuracy. Let us review this new and crucial sequence of events (Figure 4).

How did Hubble measure the distance to the Andromeda Galaxy? From the recognition and observation of Cepheid-type variable stars. These giant evolved stars have a characteristic light variability which makes them a reliable standard candle; that is to say, they can be spotted at a great distance and compared to nearby and known examples for which we know the distance. Cepheids are 100 000 times more luminous than the Sun and thus can be seen from very large distances.

In 1912 American astronomer Henrietta Leavitt (1868–1921), of Harvard College Observatory, had established a tight relationship between the luminosity and the period of variability of Cepheids: the more luminous the star is, the longer is the period—the latter spreading between a few days to about 60 days [21]. At first and like his colleagues, Hubble was searching for novae and he found more

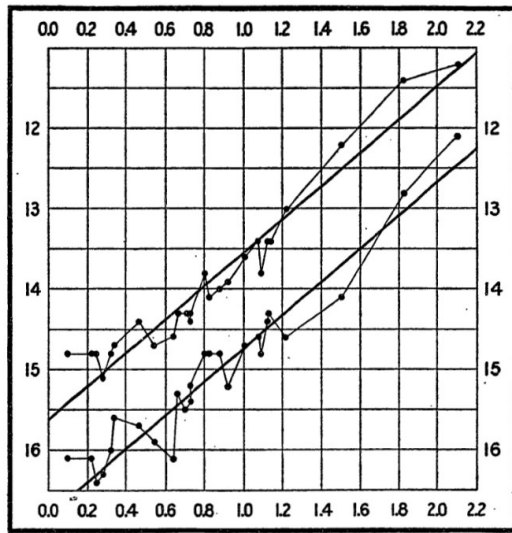


FIG. 2.

Figure 4: Observed relationship between the luminosity (in magnitudes) of Cepheids and the logarithm of their period (days) by Henrietta Leavitt. The top line is for the brightness at its maximum and the lower line at its minimum. Credit: Harvard College Observatory Circulars (1912).

of them. However, near the end of 1923, he noted that some already faint suspected novae did not disappear after a few weeks as expected, but stayed pulsating. In the first few months of 1924, Hubble came to recognize the variables for what they were: Cepheids (Figure 6).

Edwin Hubble had succeeded in photographing Cepheid variables in Messier 31 using the large 2.5-m telescope at the Mount Wilson Observatory in California. Adding data from the archival plates obtained by other astronomers with the 1.5-m, he established the distances of a few dozen of these Cepheids. On 23 November 1924, the *New York Times* reported briefly on the discovery by "Dr Hubbell" (sic). The official announcement took place at the meeting of the American Astronomical Society at the end of December 1924, which Hubble did not attend in person. Hubble reported his results in two very brief articles at the beginning of 1925: he placed Messier 31 at least 930 000 light years from the Sun, therefore clearly outside the Milky Way [22].

Without fanfare, Hubble had put an end to an age-old debate: that between the defenders of the local hypothesis of nebula, claiming that they were located inside a super Milky Way, and

of the proponents of the extra-galactic nature of the majority of nebulae [23].

Historian Michael Hoskin provided a detailed overview of the debate and related events, qualifying some of the analyses as "historical romance" [24].

There is an interesting aside to the story. Cepheids had been observed previously in Messier 31 and Messier 33 by a few other astronomers, but they had not been recognized as such [25]. It was the merit of Hubble to do so. This illustrates something that happens regularly in the history of science: objects or phenomena may have been seen several times before being discovered!

Why a divergence of views?

What was the reason for the divergence between these two camps? For several centuries, astronomers were unable to elucidate the nature of nebulae. Were they diffuse clouds of ethereal substance or independent star systems like the Milky Way? An exact determination of their distances was an absolute and necessary step to resolve the question.



Figure 6: Plate H335 of Messier 31 taken on the night of 5-6 October 1923 by Hubble who had marked three novae as "N", later deleting the top one for "Var!" when he re-identified it as a Cepheid. Credit: Carnegie Observatories.

This was the contribution of Hubble in 1924–25. We now know that a minority of objects like the Orion Nebula are real gas clouds that reside within the Milky Way and are sites of star formation; hence they present the appearance of mix of gaseous material and stars. But the majority like the Andromeda Galaxy and the famous Whirlpool Galaxy are immense and independent star systems, external to our Milky Way. For the largest galaxies, hundreds of billions of stars are held together by gravity over volumes of 100 000 light-years or more in diameter.

A few more comments on Edwin Hubble. He was a well-prepared astronomer. Delayed by the Great War, he had obtained his PhD from the University of Chicago in 1921; his thesis subject was “Photographic Investigations of Faint Nebulae”. Hired at the Mount Wilson Observatory in 1919, Hubble had access to its two large telescopes, the famous 1.5-m and the 2.5-m (primary mirror diameters). Surprisingly, Hubble was not considered a good observer. For example, his colleagues noticed that several of his photographic plates were not in optimal focus. Otherwise, he was methodical and cautious in his interpretations. He was also proud, but jealous and defensive about his contributions with respect to those of others. No one denied his self-confidence.

Expanding the universe in two stages

In the 1950s, the German astronomer Walter Baade, working in the United States, identified two types of Cepheids with distinct luminosities. It was as if previous astronomers had been confusing two rulers. Hubble observed the brightest ones, but relied on the distances of the faintest ones. The consequence was a dramatic multiplication by Baade of almost three times for the distances initially derived [26]. Today the distance to the Andromeda Galaxy is well established by a set of indicators including the Cepheids. At 2.5 million light years away, our galaxy’s sister companion measures more than 100 000 light years across and contains several hundred billion stars.

This story is not over.

A century ago, the astronomical community was witnessing an avalanche of discoveries and proposals which completely transformed our vision of the universe. Albert Einstein had put forward his theory of general relativity (GR) in 1915. Also 100 years ago, young Russian physicist Alexander Friedmann (1888–1925) re-examined Einstein’s equations of GR. Unlike Einstein’s stationary and stable solutions to these equations, Friedmann demonstrated that space-time is unstable [27]. Just like you can’t easily balance a pencil on its tip, space is either contracting or expanding. Unaware of his Russian colleague’s work, the young Belgian cosmologist Georges Lemaître (1894–1966) also found Friedmann’s solutions to the equations of GR, but he went much further. On the basis of preliminary data of distances and speeds of a few dozen galaxies (some from Slipher’s spectroscopic work), Lemaître concluded in 1927 that the actual solution is that the universe is expanding. Furthermore, Lemaître imagined in a flash of genius the expansion in reversal and proposed a stunning scenario for the origin of the universe. In a short publication in the British scientific journal *Nature* in 1931, he asserted that everything that exists was born in an extremely small and hot quantum packet of supremely condensed matter several billion years ago [29]. This was the “primeval atom” hypothesis, which today has become the Big Bang Theory.

To Hubble is attributed the discovery of the expansion of the universe, justifiably due to the work with his meticulous colleague and most competent observer Milton Humason (1891–1972). Hubble and Humason established the relationship between the distances of galaxies and their recession velocities [30]. On the expansion of space, Hubble remained doubtful until his death. Allan Sandage (1926–2010), Hubble’s young colleague for years, was categorical: Hubble never believed in the reality of expansion [31]. The discoverer of a phenomenon may not subscribe to the most accepted interpretation of it.

In less than a decade, our view went from a fixed and eternal universe to a fantastically large universe, where everything is swept away in a movement of recession of the major components of the cosmos.

Youthful memory

In 1961, I was residing and studying at a Quebec classical college; I was 17 years old. I had read in an American astronomy magazine that astronomer Allan Sandage had just published a superb atlas illustrating the galaxies [32]. In a move that I have never clarified, my mother ordered *The Hubble Atlas of Galaxies* from the Carnegie Institution of Washington; the atlas cost 10.00 USD. I spent hours and hours studying the book with my stammering English. Trying to capture these colossal stellar assemblages in my imagination, I was dazzled by their varied shapes and amazed by their elegant silhouettes. The photographs taken with the largest telescopes of the time were sublime, and I still find them fascinating and full of enigmas. Now, from time to time, I leaf through the atlas, which is kept as a precious possession. Later, I devoted several decades of my career to research on galaxies.

In conclusion

In a century, the geometrical volume of the observable universe has multiplied a million billion times ($\times 10^{15}$). On large scales, the expansion of the universe carries away galaxies like floating ice. But gravitational attraction continues to dominate at distances of a few million light years or less. Galaxies can thus assemble in small groups or form clusters of several thousand galaxies. They can also fall on top of each other and merge. This is what will happen to the Milky Way and the Andromeda Galaxy in 4 or 5 billion years; our two spirals will collide to form a large elliptical type galaxy [33].

From now on, we can affirm that 100 years ago we discovered the world of galaxies, its immensity and its strange dynamics. It is striking to remind ourselves that this discovery happened so recently. For example, my grandparents were born just a few years before Edwin Hubble and were his contemporaries!

Acknowledgements

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Further reading

Additional material may be found in an online article by the author at <https://cambridgeblog.org/2017/12/100-years-ago-the-world-of-galaxies-in-the-making/>

I see the moon and the moon sees me

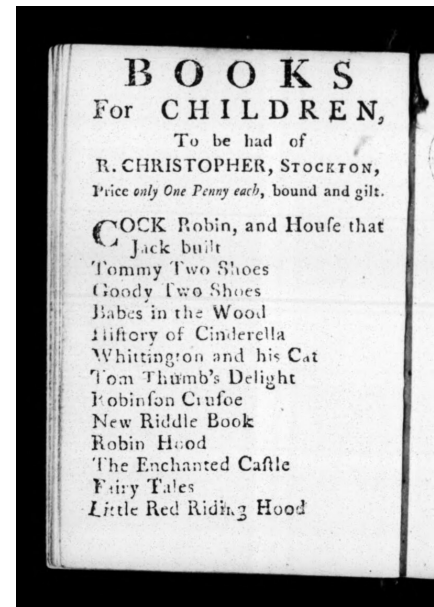
Song lyrics by Meredith Wilson (1902–1984)

Over the mountain, over the sea
Back where my heart is longing to be
Please, let the light that shines on me
Shine on the one I love

I see the moon, the moon sees me
Down through the leaves of the old oak tree
Please let the light that shines on me
Shine on the one I love

I kissed the rose, the rose kissed me
Fragrant as only a rose can be
Please take the kiss that comforts me
Back to the one I love

The nursery rhyme *I see the moon* appeared in the anthology of children's nursery rhymes, *Gammer Gurton's Garland*, published in 1783 in Stockton-on-Tees, Great Britain. The couplet was used as the basis for a popular song, penned by American musician Meredith Wilson in 1953. It was first recorded by the English group *The Stargazers* and reached number 1 in the charts. It has been recorded a number of times since, notably by Nancy Sinatra, a decade later in 1963.



The first page of contents of *Gammer Gurton's garland: or, the nursery Parnassus. A choice collection of pretty songs and verses. For the amusement of all little good children, who can neither read nor run.* 1795 edition. (Wikimedia Commons)

