

Williamina Fleming and the Harvard College Observatory

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Scottish-born astronomer Williamina Paton Stevens Fleming (1857–1911) worked closely for three decades with the Director of Harvard College Observatory (HCO), Edward Charles Pickering (1846–1919). Fleming performed a pivotal role in the Henry Draper Memorial project on stellar spectra and led the Harvard team of female computers, serving as the observatory's Curator of Astronomical Photographs between 1899 and 1911. This paper reviews her contribution to the growth of HCO and her leadership of Pickering's women assistants using archived correspondence, journals, annual reports, and contemporary accounts. Her mentoring role is examined particularly in regard to Annie Jump Cannon (1863–1941) who succeeded her at Harvard and further developed the Harvard spectral classification system. A new assessment of the contribution made by Fleming to the success of Pickering and the HCO is discussed.

1. From Dundee, Scotland, to Cambridge, Massachusetts

Williamina Paton Stevens was born in Dundee, Scotland, on 1857 May 15, the fifth child (of ten) of Robert Stevens (1826–64) and Mary Walker (1832–1910). She had seven brothers and two sisters but infant mortality claimed four of the boys.¹ Her father was a craftsman and early pioneer of photography in Dundee.

An accident with a railway delivery wagon early in 1864 when she was only six years old seriously crushed her left ankle. Doctors advised amputation at the knee but her father insisted they should try to save her leg. He did not live to see the results of his advice as he died in March that year.² For several years Mina (as she was usually called) needed a steel-reinforced leather boot for support.

At the age of 10 Mina was diagnosed with a heart weakness and spent a year in Woodside, a children's hospital. During this time she learned the value of appreciating small gifts and resolved to be kind towards children in similar difficult circumstances.³

She became a student teacher at age 14, thereby avoiding employment at the jute mills and marmalade factories in the city.⁴ By the time of her marriage in 1877 May to James Orr Fleming (1841–1900), a widower from Paisley with a career in merchant banking, her older brother Robert was planning his emigration to America. He was followed in due course by most members of the Stevens family; only her married older sister Mary would remain in Scotland.

Mina's marriage seemingly came under strain after the traumatic loss of a first son. In 1878 December she boarded a steamer to Boston, Massachusetts, following in her brother's footsteps. A month later she conceived for the second time and was three months pregnant by the time of Robert's April wedding in Cambridge.⁵ Although the record is not clear, it seems that her husband left her, went to live in New York, and remarried.

Around this time Mina worked as a housemaid for Edward and Lizzie Pickering and part-time at HCO. She then returned to the family home in Dundee where her son was born on 1879 October 6. She named him Edward Charles Pickering Fleming.⁶ Mina remained in Dundee for 18 months before sailing again to Boston in 1881 April, leaving her son in the care of her mother; it would be over six years before they would follow her.

Edward Charles Pickering (1846–1919) came from a distinguished New England family based in Boston. During his twenties he developed the first instructional laboratory in physics at the Massachusetts Institute of Technology (MIT). In 1870 he was experimenting with sound telegraphy and accompanied Joseph Winlock (1826–75), the third director of HCO, to Spain for the December solar eclipse.

In 1874 Pickering married Lizzie Wadsworth Sparks (1849–1906), the daughter of historian and former Harvard University President Jared Sparks (1789–1866); they had no children. Winlock died in 1875 June and Edward Pickering was appointed the fourth director of HCO in 1877 February at a salary of \$3400 (equivalent to about £61,000 today).^{7,8}



Fig. 1: Williamina Fleming, seen here around 1895 when she would have been aged 38, became the leading female astronomer at Harvard College Observatory (HCO) in the late 19th and early 20th centuries. Edward Pickering, seen here around 1880 when he would have been aged 34, was the fourth Director of HCO from 1877 to 1919. (Institute of Astronomy, University of Cambridge)

2. Harvard College Observatory in 1877

Harvard College Observatory was established in 1839. In 1845 it moved to a new site and two years later mounted a 0.38-m refractor by Merz and Mahler (a twin of the one in Pulkowa Observatory) in the Sears Tower, courtesy of the citizens of Boston who raised \$25,730 (*c.* £460,000 today).⁹

The initial director of HCO, William Cranch Bond (1789–1859), facilitated the first daguerreotype image of a star (Vega) in 1850. Seven years later, using collodion plates and an improved driving clock, his son George Phillips Bond (1825–65), later to become the second HCO director, made a photographic study of Mizar and Alcor. He reflected: ‘On some lofty mountain and in a purer atmosphere we might, with the same telescope, include the 8th magnitude ... measure the relative magnitudes of the stars ... distances and angles of position of double stars ... as exact as the best micrometrical work.’¹⁰

Winlock succeeded the Bonds but did not continue with stellar photography. Instead, American interest in astrophotography was taken up by Lewis Morris Rutherford (1816–92) and Henry Draper (1837–82). The work of the latter became inextricably linked with HCO after the arrival of Edward Pickering as its fourth director.

2.1. Harvard astronomers

When Pickering took up his post in 1877 February there were four astronomers under his direction. Arthur Searle (1837–1920) had begun in 1868 and was

temporary director after Winlock. William Augustus Rogers (1832–98) started in 1870. Leonard Waldo (1853–1929) and Joseph F. McCormack (1854–80) were also assistants. By 1880 Pickering had recruited Winslow Upton (1853–1914), Oliver Clinton Wendell (1845–1912), and John Rayner Edmands (1850–1910).

Observatory income consisted of \$175,000 from endowments and \$14,000 from sale of a time service (*c.* £3.4 million total today). At this time a copyist or computing assistant could be hired for \$500 per year or 25 cents per hour (*c.* £9000/year today).¹¹

HCO policy had changed in 1875 to admit women staff and three were appointed to assist Rogers; these included his wife and also the eldest daughter of the deceased director, Anna Winlock (1857–1904), who was an excellent mathematician. A fourth computer for Rogers began in 1879: Selina Cranch Bond (1831–1920), the daughter of the first director of HCO, who would give loyal service for 27 years.

2.2. Instruments and observing programmes

To accompany the 0.38-m equatorial Winlock ordered a 0.20-m meridian circle from Troughton & Simms which was installed in 1870. The ‘great refractor’ was essentially a visual instrument occupied in photometric observations of the newly discovered Martian moons and the satellites of Jupiter and Saturn. HCO had responsibility for helping revise F. W. Argelander’s *Bonner Durchmusterung*.¹² This involved measuring positions with the meridian circle for all stars to 9th magnitude in one northern zone (50–55°) which was the primary responsibility of Rogers and his team of computers.

Table 1: Female assistants at Harvard College Observatory 1875–1911

No.	Name	Dates	Yrs.	Notes
1	Mrs R. T. Rogers	1875–98	23	Wife of William A. Rogers
2	Miss Rhoda G. Saunders	1875–88	12	
3	Miss Anna Winlock	1875–1903	28	(1857–1904) Mathematician. Daughter of Joseph Winlock
4	Miss Selina Cranch Bond	1879–1906	27	(1831–1920) Daughter of W. C. Bond and sister of G. P. Bond
5	Miss Nettie A. Farrar	1881–86	5	Married and moved to Texas
6	Mrs Williamina P. Fleming	1881–1911	30	(1857–1911) Named her son Edward Charles Pickering Fleming
7	Miss Louisa Winlock	1886–1915	29	(1860–1916) Daughter of Joseph Winlock, sister of Anna
8	Miss R. W. Gifford	1886–88	2	Brother assisted Willard P. Gerrish
9	Miss Louisa D. Wells	1887–1933	46	‘Tiny and vehement’ [CPG]
10	Miss Annie E. Masters	1887–89	2	Former teacher and book-keeper
11	Miss Jennie T. Rugg	1887–89	2	
12	Miss Nellie C. Storin	1887–96	9	
13	Miss Antonia Maury	1888–1933	Part time	(1866–1952) Niece of Henry Draper. BA Vassar, 1887. ‘A dreamer ... denouncing injustice’ [CPG]
14	Miss Florence Cushman	1888–1937	49	(1860–1940) ‘A dignified galleon of a woman’ [CPG]
15	Miss Mabel C. Stevens	1888–1906	18	Took Radcliffe entrance exam, but insufficient finances
16	Miss Edith F. Gill	1889–?	31+	Sister Mabel joined three years later. ‘Hover in the background’ [CPG]
17	Miss Lillian L. Hodgdon	1889–1939	50	‘Volatile strutting hen’ [CPG]
18	Miss Evelyn F. Leland	1889–1925	36	(c.1870–1930)
19	Mrs Imogen Willis Eddy	1889–1904	15	(?–1904) Died in fall from elevator. Two years’ work for B. A. Gould
20	Miss Amy Jackson McKay	1891–1907	16	(?–1907) Died after 6-month illness
21	Miss Harriet I. Stevens	1891–1910	19	
22	Miss Mabel A. Gill	1892–?	28+	Sister of Edith. ‘Quiet ... always busy’ [CPG]
23	Miss E. Gertrude Wolfe	1893–99	6	Retired with eyesight problem
24	Miss Ida E. Woods	1893–?	27+	‘A stickler for protocol ... a sense of being slightly superior’ [CPG]
25	Miss Annie Jump Cannon	1896–1940	47	(1863–1941) BA Wellesley 1878, MA 1907
26	Miss S. J. Hall	1897–1900	3	Became Mrs Bonesteel in 1898
27	Miss Sarah E. Breslin	1898–1912	14	
28	Miss Darsie C. Bard	1899–1900	1	
29	Miss Maude E. Harriman	1900–05	5	
30	Miss Marion F. Michaelis	1900–06	6	
31	Miss Henrietta Swan Leavitt	1902–21	19	(1868–1921) Volunteer in 1895. BA Radcliffe, 1892
32	Mrs Johanna C. S. Mackie	1903–20	17	(1860–1943) Mina’s sister
33	Miss Katherine Searle	1904–12	8	Related to Arthur Searle. BA Radcliffe, 1901
34	Miss Ida May Stevens	1904–09	5	(1882–?) Mina and Johanna’s niece. Became Mrs Garret in 1907
35	Miss Grace R. Brooks	1906–20	14	
36	Miss Alta M. Carpenter	1906–20	14	
37	Miss Mollie E. O’Reilly	1906–18	12	Became Mrs Sloan in 1918
38	Miss Arville D. Walker	1906–?	14+	‘Billy’
39	Miss Mary E. Howe	1907–09	2	
40	Miss Margaret Harwood	1907–12	5	(1885–1979) 6 months/year. BA Radcliffe, 1907. Became first director of Maria Mitchell Observatory in 1912
41	Miss Ruth C. Waterbury	1907–10	3	
42	Miss Marion C. Whyte	1911–13	2	

This table omits women who spent < 1 year at HCO, e.g. Mary Wagner (1893 September–December).
[CPG] = Cecilia Payne-Gaposchkin (1900–1979) who began working at HCO in 1927. Quotes about some female computers are from her autobiography, published by CUP in 1984.

In Pickering’s first *Annual Report* (1877) an appendix describes the work of other American observatories with the conclusion that work on photometry was unexplored territory and the resolution ‘to determine the brightness of all the heavenly bodies, so that all may be compared with a single standard.’¹³ Local instru-

ment makers Alvan Clark & Sons were recruited by Pickering to construct a 40-mm f/20 meridian photometer. During 1878 over a dozen photometer designs were tested on the 0.38-m equatorial by Pickering, Searle, and Upton, while Rogers was completing his observations of some 8000 zone stars with the meridian circle.

2.3. Pickering's early success

To keep HCO telescopes fully employed Pickering initiated a public subscription funding scheme to raise \$5000 a year (*c.* £90,000 a year today) for 5 years.¹⁴ At this stage he estimated the total value of HCO to be around \$300,000 (*c.* £5.4 million today).¹⁵

During 1879 various maintenance tasks were completed including repairs to the large dome shutters and decoration of the East Computing Room for the female assistants.¹⁶ A survey of planetary nebulae using a double-image micrometer and direct-vision spectroscope with the 0.38-m refractor was accompanied by a visual survey of spectra with a 0.10-m refractor to identify stars with bright lines.¹⁷

Observations of 4260 stars with the 40-mm meridian photometer occupied Pickering for typically four hours on clear nights using a polarization method visually to compare two stars. The *Harvard Photometry* catalogue (HP) containing the results of these observations would be published in 1884 (*Harvard Annals* vol. XIV), earning him his first RAS Gold Medal two years later.¹⁸

3. The sixth female assistant at HCO

Four female computers were fully occupied by Rogers on reduction of his zone observations. In 1881 first Nettie Farrar and then Mina Fleming began at HCO.¹⁹ Their initial work involved copying and computing tasks for Volume XIII of the *Harvard Annals* and publication of Winlock's micrometric measures with the 0.38-m refractor.

Ladies were not allowed to use the telescopes at night, but a daytime opportunity arose in 1882 December when the transit of Venus was observed through thin cloud. It was likely that the lady computers were invited to view the transit through at least one of the six telescopes in operation while the male observers were busy recording contact times.²⁰

Farrar and Fleming had started working on the first part of Volume XIV of the *Annals*, supplying copy for the *Harvard Photometry* catalogue to the printers regularly throughout 1883. Edmands assumed responsibility for the HCO Library at this time and would have supported them.

During 1884 Mina moved on to Part II of Volume XIV which included a literature review from old catalogues, going back to Ptolemy and Herschel; this work included discussion of sources of error, which would have given her a better understanding of the nature and requirements of astronomical research. Pickering was clearly pleased with the speed and accuracy of her work on the *Annals*.

3.1. The influence of Henry and Anna Draper

In 1867 Henry Draper, a physician and professor of chemistry, married Mary Anna Palmer (1839–1914). In 1874 she inherited significant wealth from her father's

real-estate business. For 15 years the Drapers collaborated on observations, photography, and laboratory work. In 1872 they succeeded in capturing the spectrum of Vega showing four absorption lines through a 0.70-m reflecting telescope with a quartz prism and wet plates.²¹

By 1880 the Drapers were using dry plates for their photographic work with a 0.28-m Clark refractor, and in 1881 March recorded an image of the Orion Nebula. However, in 1882 November Henry Draper died from double pleurisy.²²

Five days before his early demise the Drapers hosted a dinner party at their New York mansion for 40 leading scientists and friends. Pickering used the opportunity to encourage Draper to publish his work on stellar spectra, offering the services of HCO to assist in their measurement and reduction. This offer was repeated in 1883 January by letter to his widow.²³

Mrs Draper visited HCO in February, bringing with her 21 plates containing tiny stellar spectra 6 mm long. These were measured by Pickering who then presented the results to the American Academy of Arts and Sciences in April.²⁴

3.2. Early experiments on stellar photography

In 1882 Pickering secured \$500 funding (*c.* £9000 today) for a method to estimate the brightness of stars using stellar photography.²⁵ His younger brother, William Henry Pickering (1858–1938) from MIT, began photographic tests with a 0.17-m f/5 portrait lens in December that year; 462 stars to 9th magnitude were recorded but the star images proved large and distorted.

Improved results using a 50-mm f/3.5 Voigtländer lens in a driven 30-minute exposure revealed stars of 8th magnitude in a region 15° square. These Harvard experiments began just a month after David Gill (1843–1914) and Edward Haggard Allis (1849–1911) succeeded in imaging comet C/1882 R1 with a 63-mm f/4.5 doublet lens in driven exposures of 30 to 140 minutes.²⁶

3.3. Pickering in Europe in 1883

After six years' work at HCO Edward and Lizzie Pickering sailed to Europe in the summer of 1883 for their first vacation. Pickering visited many of the main European observatories, delivered a key presentation to the RAS in London, and examined catalogues produced by Sir William Herschel (1738–1822).²⁷

It seems probable that his extensive tour of European observatories was partly intended to review equipment and techniques in each country and partly to gauge the strength of the competition.²⁸ At the June RAS meeting Pickering, newly appointed as a Foreign Associate, presented a seminal paper: *On the determination of the light and colour of the Stars by Photography*.²⁹

In this, many key aspects of the future Harvard approach were outlined: comparing modern photometric catalogues with historical records; imaging large fields on a single plate; capturing three types of image

(star dots, trails, and spectra) in a time-efficient manner; preparing a series of photographic maps of the whole heavens to identify new stars; and investigating the colour of stars using plate sensitivity. Responding to a question from the Astronomer Royal, William Christie (1845–1922), Pickering showed a photograph of stellar spectra but chose not to reveal further details.³⁰

4. Funding developments and ‘some plan of cooperation’

Securing new sources of funding was now essential for HCO. The 5-year subscription fund had ended and declining interest rates were undermining endowment returns. During 1884 five male assistants were made redundant, effectively ending the visual study of spectra.

Pickering and Wendell began testing a new 100-mm meridian photometer which would extend the work of the first Harvard Photometry. In spring of 1885 a second series of stellar photography tests began using a 60-mm 30° objective prism. With this, 100 spectra were imaged on a single plate to 8th magnitude in a 1-hour exposure.³¹

Following the death of her husband, Anna Palmer Draper initially planned to hire two assistants to continue their spectral work at the Hastings Observatory, New York. Pickering suggested several possible recruits but inwardly hoped that HCO at Cambridge might continue in some way the Drapers’ pioneering approach.

In 1885 May Pickering explained his plans for ‘a somewhat extensive piece of work in stellar photography ... I wish to ask if you would not like to enter upon some plan of cooperation by which Dr. Draper’s name should be associated with the work ... maps of the heavens from which the position, brightness variability and (indirectly) the colour of the stars could be determined’.³² Agreement in 1886 February on a joint venture heralded a major new direction for HCO for decades to come and created an unexpected opportunity for the sixth female assistant at Harvard, Mina Fleming.³³

4.1. *The 0.20-m Bache astrograph*

By 1885 June Pickering had secured a \$300 grant from the Rumford Fund and \$2000 from the Bache Fund (total *c.* £41,000 today) to extend his photographic investigations. A Voigtländer doublet (Petzval) lens of 0.20 m aperture was refigured by the Clarks to produce an *f*/5.6 astrograph and was mounted equatorially (Fig. 2).

The brass lens cell was fixed in a steel tube mounted in trunnions on a large fork with a clockwork drive. It was erected in a transit shed with a 0.60-m slit allowing plates to be taken for up to 40 minutes across the meridian. The plate scale of 1° per 2 cm gave coverage of 12° in declination and 10° in right ascension. This scale matched exactly the *Bonner Durchmusterung* (BD) charts; when enlarged three times they matched the

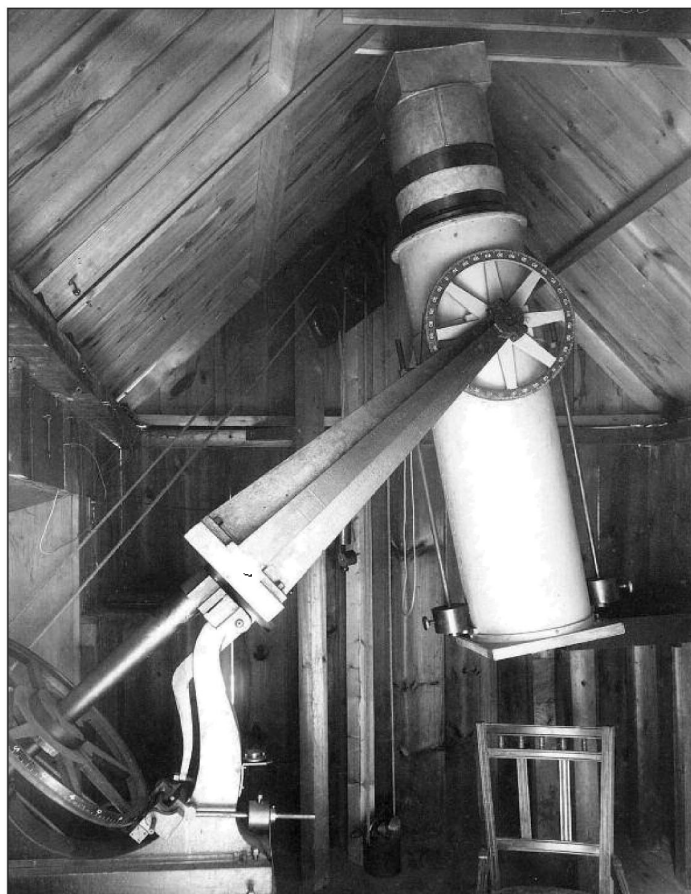


Fig. 2: The 0.20-m *f*/5.6 Bache astrograph was first used at Cambridge in 1885. After three years it was moved to Colorado for site testing and then Chosica in Peru, before being installed at Arequipa in 1890. (UAV 630.271, (8), E230, Harvard University Archives)

scale of 1 arc-minute per millimetre used by Peters and Chacornac for their ecliptic charts.³⁴

Pickering devised three types of work: star trails; driven exposures for charts; and spectral study. Experiments showed that 30-minute star trails reached 14th magnitude near the pole but only 8th magnitude at the celestial equator.

Photographic magnitudes were determined for 117 stars within 1° of the pole by Nettie Farrar; only 38 stars were listed in the BD for this region. The nebulosity around Maia in the Pleiades, detected by the Henry brothers in Paris in mid-November, was subsequently found on a plate taken a fortnight earlier in Cambridge. An investigation of the spectra of members of the Pleiades began in 1886 January.³⁵

Pickering calculated that the Bache astrograph could produce 2000 plates annually, if operated for ten hours per night and four nights per week. He further reasoned that with two such astrographs in different hemispheres, and utilizing only the central 5° square region of each plate, mapping the whole sky in a single year would be possible with 1600 plates.³⁶

With the imminent arrival of support from Mrs Draper it was now possible for him to believe he could chart the heavens with a veritable army of instruments: photometer, astrograph, and spectroscope. However the data generated by these surveys would be unprecedented and a team of computers would be essential.

4.2. *The Henry Draper Memorial (HDM)*

Anna Palmer Draper agreed to support a photographic study of stellar spectra at HCO as a memorial to her husband. Initially this involved a \$1000 gift and \$200 per month (*c.* £18,000 and *c.* £3600 a month today).³⁷

Willard Peabody Gerrish (1866–1937) was recruited in 1886 February to begin taking plates.³⁸ A cottage was later refurbished as a darkroom, with the three-times enlarged copies transferred to the HCO computing rooms and mounted for daylight illumination. Stars were identified by comparison with the *Bonn Atlas*, and stellar spectral lines were compared with the solar spectrum.

Mrs Draper donated her 0.28-m *f*/14 Clark refractor with corrector lens for photographic use in 1886. A year later this was followed by the other Draper instruments, a 0.38-m mirror and a 0.70-m *f*/5 reflector. New mountings were constructed by George Bassett Clark (1827–91) and they were mounted in two wooden observatories with 6-m domes where they were used for taking photographic spectra of bright and faint stars respectively.

The mean dispersion achieved with HCO instruments varied from 300 Å/mm for the Bache astrograph fitted with a 13° prism to 45 Å/mm with a 15° prism on the Clark refractor; the addition of three similar prisms increased the dispersion to 11 Å/mm for first- and second-magnitude stars.³⁹ The Bache astrograph produced spectra 1 mm wide by introducing a driving clock error of 12 seconds in either a 5-minute or 1-hour exposure for 6th- or 8th-magnitude stars respectively.⁴⁰

The primary aim of the HDM project was to produce a catalogue of spectra of bright stars of the entire sky visible from Cambridge north of –24° declination. On each plate three or four exposures of 5 minutes were taken of areas 10° square; typically 40 spectra of 6–12 mm length and 1 mm width could be classified, except in the case of red stars which appeared fainter. By 1887 March Pickering was able to report that 308 plates had been measured and 11,287 spectra identified; 99 plates exposed for 1 hour revealed 2974 spectra. In all 15,729 spectra were obtained with the Bache astrograph in the first nine months.⁴¹

4.3. *A new challenge for Mina Fleming*

In 1886 October Pickering informed Mrs Draper of the successful mounting of the 0.28-m Clark refractor and the expenditure to date on the Draper Memorial Fund.⁴² At this stage 137 Bache plates of 5 minutes exposure and 87 of 60 minutes exposure had been taken. One hundred and ninety plates had been measured and

6769 spectra recorded; about 3000 stars had been identified and their names entered opposite each.

Pickering explained: ‘Mr. Gerrish attends to the photographic work and receives \$50/month ... Miss Farrar measures the photographic plates at 30 cents/hour. Miss Winlock copies and computes at 25 cents/hour.’⁴³ Louisa Winlock had become the seventh female computer at HCO, joining her sister on the staff; later she was joined by Miss R. W. Gifford whose brother supported Gerrish during each clear night. Mrs Draper was effectively now funding an increasing number of HCO assistants for the HDM catalogue.

At the end of the year Pickering informed her: ‘Miss Farrar who has measured all the plates until recently, is about to get married ... she is now instructing Mrs. Fleming who has assisted me, and who will I think take her place satisfactorily.’⁴⁴

In practice Mina had already shown an aptitude for examining the Bache plates. Earlier in the year she had made the important discovery of two Wolf–Rayet (WR) stars after noticing bright lines in a couple of faint spectra on a plate taken of the Cygnus region.⁴⁵ At this time there were 13 known WR stars of which three had been found visually by Pickering five years earlier. Mina’s discovery was reported in *Nature* in 1886 September.⁴⁶

At the end of 1886 Mina became responsible for the examination, physical care, classification, and indexing of thousands of glass plates. For the next 25 years she made herself indispensable to the success of HCO and gained an international reputation for her astronomical work.

5. Expansion of HCO

Having struggled to find sufficient funding for many years Edward Pickering gained control of two new bequests in 1887. One of these, the \$230,000 Boyden Fund (over £4 million today), was for the establishment of an astronomical observatory on a mountain peak.⁴⁷ The 0.33-m *f*/14 Boyden refractor made by the Clarks included a reversible crown lens to enable both visual and photographic work. The other, the \$300,000 Paine legacy (*c.* £5.4 million today), covered the Paine Professorship of Practical Astronomy chair that was held by Pickering and also routine HCO expenses.⁴⁸ Mrs Draper had also increased her contribution fourfold to \$10,000 per annum (*c.* £180,000 today) for the Henry Draper Memorial.

Optimistically Pickering also advertised in 1888 November for a \$50,000 (*c.* £900,000 today) donation to construct a much larger photographic telescope. His plan for a 0.60-m *f*/5.5 instrument with a 4-element objective capable of reaching 16th magnitude became a reality 5 years later.

Additional staffing expanded the productivity of HCO. In 1887 William Pickering transferred from MIT to lead the new Boyden Department. Edward Skinner

King (1861–1931) graduated from Hamilton College, New York, and joined the HCO team; he soon began supervising the photographic work at Cambridge. The third new astronomer was Solon Irving Bailey (1854–1931) who would play a major role in establishing the Boyden Station in the southern hemisphere. Four women computers were also recruited by Pickering in 1887. Of these, Louisa Wells worked at HCO for 46 years.

5.1. *The search for a mountain site*

In 1876 Edward Pickering supported the formation of the Appalachian Mountain Club. Both his brother William and John Edmands shared this adventurous spirit and an 1887 summer expedition by them all to 4300-m Pike's Peak in Colorado was organized. Site-testing included meteorological surveys together with assessment of the atmospheric seeing and transparency, for which a 0.30-m refractor was used.

A second exploratory trip the following year included both the Bache astrograph and the Boyden refractor. More sites in Colorado were tested together with California where they photographed the solar eclipse in 1889 January. The group then split up. William Pickering took the Boyden refractor to Mount Wilson while Solon Bailey and his family travelled much farther south to Peru and Chile on a two-year expedition with the Bache astrograph.

A mountain site at 2027 m was selected north of Chosica, Peru. In four months 1200 plates were taken with the Bache astrograph, extending the photographic and spectral surveys to the south celestial pole. While his brother Marshall completed the photographic work, Solon Bailey used Pickering's 100-mm meridian photometer to make 26,000 measures of the brightness of 6700 southern stars.

During the cloudy months of 1889 September and October the brothers investigated other potential sites, eventually deciding that one near Arequipa offered the best opportunities for the southern hemisphere Boyden Station. Arequipa was a small town surrounded by desert near the extinct volcano El Misti; the site was at 2457 m elevation and latitude 16° 24' south.⁴⁹ The Boyden Station in Peru would operate for 36 years and be of immediate use to Pickering for the Harvard photographic map of the heavens.

5.2. *The Carte du Ciel*

Development of the Carte du Ciel, including the contributions of David Gill at the Cape of Good Hope and Amédée Ernest Barthélemy Mouchez (1821–92) at Paris Observatory, has previously been described by the author.⁵⁰ Edward Pickering did not take up the invitation from the French Academy of Sciences to attend the first International Astrophotographic Congress held in 1887 April at which the Carte du Ciel project was discussed.⁵¹ But he did offer several recommendations based on the experience at HCO, and he offered to help with the photometric results.

In choosing not to attend the Paris Congress Pickering neatly avoided the vast majority of pitfalls that subsequently undermined the Carte du Ciel project. His decision was justified by the absence of direct government funding to American observatories; the Harvard Corporation were already managing several large bequests for astrophotography and Pickering was planning to upgrade to a 0.60-m f/5.5 instrument.

He would not have known that the Government of the French Republic had already chosen to commission the 0.33-m f/10 astrograph design for the Carte du Ciel which would effectively limit the photographic fields to 2° square, whereas he preferred a 5° field. However he would have suspected that Gill would push for observatories to produce a catalogue and not just a chart of the heavens, as was indeed the case.⁵²

By this time HCO had the largest team of computers in the world and Pickering intended to keep them focused on measurements for photometry and spectroscopy, enabling the history of the heavens to be captured. Distractions like the Astrophotographic Catalogue were simply not relevant.

So as Pickering began his Colorado expedition he knew the Carte du Ciel would not involve HCO and he was free to keep to his planned investigations, no doubt a huge relief. Meanwhile back in Cambridge Mina's long wait was nearing an end: in 1887 September a boy of nearly 8 years of age crossed the Atlantic with his grandmother to join his mother in Massachusetts.⁵³

6. The many roles of Mina Fleming

Mina was aged 29 and had worked at HCO for nearly six years when she took responsibility for the Draper Memorial Catalogue.⁵⁴ Initially she reviewed the existing methods of spectral classification for her analysis of the Bache plates. Pickering valued her efficiency in preparing HCO publications and chose to significantly consolidate her role in this respect.

Pickering was keen to promote HCO as a clearing-house for observational data and expansion of the number of women computers was essential to handle the increasing number of plates. Mina assumed responsibility for recruiting the majority of suitable candidates from 1888 onwards, achieving an impressive team of loyal workers many of whom would remain at HCO for decades.

Training, monitoring and planning their work schedules became a routine task. She devised a Form of Records to explain the format and expectations of clerical work required for the record-books; accuracy, speed, and legibility were essential requirements. In practice all female assistants now reported to Mina who ensured that the correct etiquette, efficiency, and discipline were maintained.

Analysis of the glass plates enabled women computers to become observers without needing to work at



Fig. 3: Women computers often worked in pairs. Here, Mabel Stevens records nebula positions in Orion measured by Mina Fleming (right). Each plate was laid on a frame tilted at 45°, and light reflected through it by a horizontal mirror. Each portion of the plate was studied with a magnifying glass, and the coordinates of objects measured by a T-square. (W289693_1, Harvard University Archives)

night in an observatory. All employees were given one month vacation per year; August was usually the least productive month due to high humidity in the summer. The women's working environment included 'two, light, pleasant rooms ... convenient writing-tables, shelves of notebooks, astronomical catalogues and reports, with their walls hung with star maps and portraits of noted astronomers ... magnifying glasses, frames for holding the plates ... [nearby] wooden boxes containing the brittle though perishable glass plates.'⁵⁵ A musical, the *Observatory Pinafore*, written by Winslow Upton in 1879, provides an alternative earlier (male) insight into HCO culture and expectations.⁵⁶

Pickering had no deputy to share his workload and increasingly relied on Mina to act in a secretarial role for correspondence; this would extend to his discussions with HCO astronomers whose work also needed to be published in the *Annals*. As the number of Bache plates rapidly increased Mina developed an efficient storage and retrieval system.

In time she would prepare papers for astronomical conferences, support HCO workshops, and develop a strong mentoring approach for her successors. Despite all of these roles demanding attention Mina maintained her ability to discover a whole host of significant astronomical objects, from variable stars to gaseous nebula, from novae to Wolf-Rayet stars, and from near-Earth asteroids to stars with peculiar spectra.

6.1. Spectral classification at Harvard

At the Collegio Romano observatory, Angelo Secchi (1818–78) had used a 0.16-m flint glass objective prism of 12° refracting angle with the 0.24-m Merz refractor to conduct his 15-year visual study of the spectra of 4000 bright stars. By 1868 his classification scheme included four classes: Type I included white and blue stars of the Sirius type with hydrogen absorption lines; Type II stars were slightly coloured with a solar-type spectrum; Type III were orange to red stars of the Betelgeuse type showing banded spectra, including many long-period variables; Type IV were red stars with absorption bands separated by bright spaces, the carbon stars.⁵⁷

Pickering had adopted the objective prism instrument at HCO so it was natural that he should further develop Secchi's system. Type V stars were announced in 1891 and included WR spectra with bright lines and planetary nebulae. Type VI stars followed in 1908, with absorption bands accompanying shorter blue wavelengths.⁵⁸

Mina was assigned several tasks. These involved:

1. Classifying and describing 28,266 spectra, representing 10,351 stars to 7th magnitude north of declination -25° , photographed on 633 Bache plates each measuring 20×25 cm;
2. Estimating the photographic stellar magnitudes by measurement of the photographic density around 432 nm using a shaded glass wedge;

3. Recording the shortest-wavelength hydrogen line visible, estimating the strength of the calcium absorption line, and the presence or absence in the spectrograms of the F line ($H\beta$) at the long-wavelength cutoff;
4. Identifying the coordinates of each spectrum using a stand and also by overlaying the plate on the *Durchmusterung*, followed by calculating the star's position for epoch 1900;
5. Applying corrections for declination, plate sensitivity, transparency of atmosphere, and driving clock irregularities, using the *Harvard Photometry* catalogue as a reference.

Each plate included up to four regions 10° square with any given star recorded on at least four photographs. Plates were placed on a stand and illuminated with natural light reflected by a mirror (Fig. 3). As the work progressed, Mina enlarged the four Secchi spectral types into 13 groups, adding group O for WR stars with bright lines, P for planetary nebulae, and Q for those not classified by A to P.⁵⁹

6.2. *New colleagues and more discoveries*

Fortunately Mina was able to enlist the support of many additional colleagues for numerical computations and clerical work, notably Louisa Winlock, Louisa Wells, Florence Cushman, Mabel Stevens, Edith Gill, Lillian Hodgdon, Evelyn Leland, and Imogen Eddy.⁶⁰ Pickering approved of Mina recruiting her team but reserved the right to add his own personnel.

His excellent links with nearby women's colleges resulted in three famous recruits. Antonia Cactano Maury (1866–1952) was trained by Maria Mitchell (1818–89) at Vassar College and graduated in 1887; Annie Jump Cannon (1863–1941) was trained by Sarah

Frances Whiting (1846–1927) at Wellesley College and graduated in 1884; and Henrietta Swan Leavitt (1868–1921) graduated from Radcliffe College in 1892.⁶¹

Maury, the niece of Henry Draper, was appointed as the 13th female computer in 1888 June. Her task was to study in detail the spectra of bright northern stars imaged by the 0.28-m Draper refractor. Spectrograms from this instrument were capable of enlargement to 60×10 cm and for Sirius revealed over 500 faint lines.

In 1887 March a plate taken of ζ Ursae Majoris had shown a doubling of the calcium K line. By 1889 January this periodic doubling had been investigated by Maury; Pickering announced the discovery of Mizar as the first spectroscopic binary the following November. Maury then found a similar pattern in β Aurigae spectra, but although credited by Pickering she felt her work deserved greater recognition.⁶²

She devised a more complex spectral classification system of 22 groups with Roman numerals and a/b/c categories. Her detailed study of the width and sharpness of spectral lines slowed the work significantly and delegating tasks to other assistants proved impossible.⁶³ Between 1891–93 she left HCO for a teaching post and a further absence in 1895 involved a trip to Europe; final publication in HCO *Annals* XXVIII came in 1897, some nine years after Maury started.⁶⁴

Between 1888 and 1890 an impressive series of discoveries flowed from HCO, with Mina Fleming central to most of them. Plate B2312 involved a 90-minute exposure with the Bache astrograph, taken in 1888 February by William Pickering. Careful inspection by Mina noted 'a semicircular indentation 5' in diameter 30' south of Zeta [Orionis]' – she had discovered the now-famous Horsehead Nebula (Fig. 6).⁶⁵

Fig. 4: Examples of stellar spectra, from the *First Annual Report of the Henry Draper Memorial*, published in 1887 March:

- (1) 4-mm Draper spectrum of Vega, 5-minute exposure with a 50-mm $f/3.5$ Voigtländer lens and 30° prism in 1882;
- (2) 9-mm Harvard spectrum of Mizar and Alcor, 5-minute exposure with 0.20-m $f/5.6$ Bache astrograph, showing the typical scale of images examined by Mina Fleming; (3) 50-mm spectrum of Vega, taken in 59 minutes with 0.28-m Clark refractor with 2 prisms in 1886 November; Antonia Maury had responsibility for investigating the spectra of the bright northern stars;
- (4) 80-mm spectrum of Pollux, 50-minute exposure with 0.28-m Clark refractor using four prisms in 1887 January.

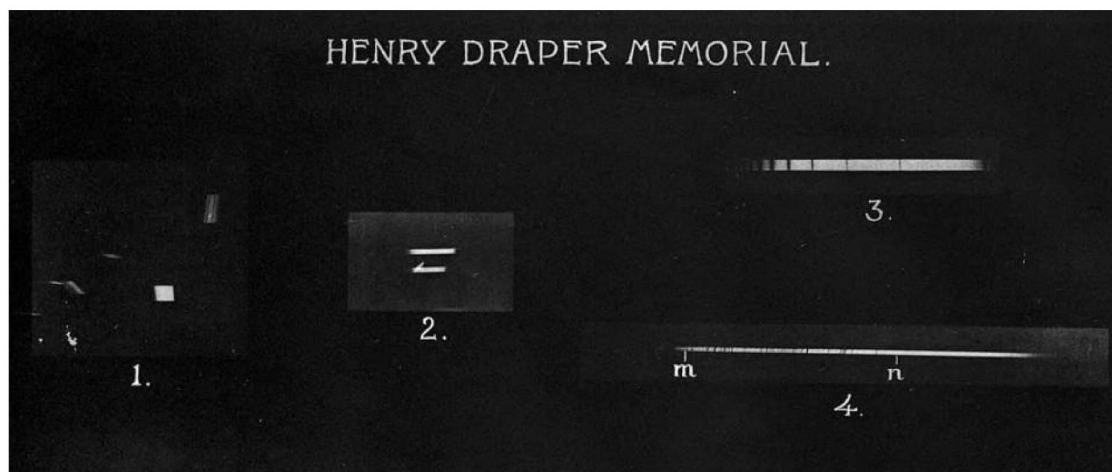




Fig. 5: Mrs Draper funded the Henry Draper Memorial project. This 1891 group includes Mina (standing, right) showing her some plate journals. The other female assistants pictured are, from left, Florence Cushman, Imogen Eddy (seated), Louisa Winlock, and Mabel Stevens. The cramped conditions in which the women worked became apparent to Mrs Draper during her visit. (W289692_1)

Pickering was keen to estimate the number of nebulae that might be discovered photographically. As a trial, he selected the region around the Orion Nebula from RA 5h 10m to 5h 50m and declination -10° to $+5^\circ$. Mina's careful scrutiny of this area, 0.4% of the whole sky, resulted in a table containing 27 nebulae. Based on this investigation Pickering estimated that 4000 to 5000 nebulae might be discovered using 400 plates.⁶⁶

Plates 2185 and 642 were used as standards in a lengthy investigation into the photographic determination of the brightness of stars.⁶⁷ In addition to star trails of the Hyades, Mina also examined 1000 stars to 15th magnitude within 1° of the north celestial pole. For this, ten series of plates photographed between 1885 August and 1888 March by the Bache astrograph, the 0.28-m Draper refractor, and the 0.33-m Boyden refractor were investigated, with 20 stars chosen as standards.

A study of stars in and around the Pleiades involved eight plates taken between 1885 November and 1888 February. For this work Mina collaborated with William Pickering and Edward King in a review of the excellent images photographed by the Henry brothers and the earlier astrometric study by Charles Wolf (1827–1918) at Paris Observatory.⁶⁸ Bright equatorial star trails also formed a significant element of this study. Star magnitudes from the *Harvard Photometry* were compared with intensity values from photographic images. Pickering postponed his final conclusions until after photometric values for fainter stars became available; this work would later be completed by Henrietta Leavitt.⁶⁹

In the second half of 1889 Bache plates from Chosica, Peru, began arriving at HCO. Mrs Draper had

commissioned a replacement astrograph for Cambridge: the 0.20-m f/6.2 Draper astrograph was mounted on a German equatorial and equipped with a 5° objective prism enabling spectra of 10th-magnitude stars to be photographed.⁷⁰

Mina scrutinized the incoming Bache and Draper astrograph plates, intent on spotting more stars with bright line spectra. Seven WR stars were found in 1889, including several near the Carina Nebula; five more followed in 1890, by which time Mina had discovered half of all known Wolf–Rayet stars.

Her keen eyesight also facilitated the discovery of variable stars. In 1889 September S Centauri was found as a 6th-magnitude star missing from catalogues. Pickering encouraged her to report findings in both the *Sidereal Messenger* and *Astronomische Nachrichten*; a series of papers announcing new variable stars in different constellations along with lists of stars having peculiar spectra began in 1890. However it would be the publication of *The Draper Catalogue of Stellar Spectra* in 1890 that would forever establish her name among the greatest of women astronomers.⁷¹

7. HCO in the early 1890s

The first 15 years of Edward Pickering's leadership of HCO were dominated by his carefully planned strategy of expansion made possible by a series of successful grant applications, bequests, and collaborations. He had elevated Harvard to the highest levels globally by securing a southern hemisphere observatory at Arequipa equipped with quality Clark instruments.

Whole-sky surveys for photometry, photography, and spectroscopy were beginning to reveal the secrets of the stars. New technology had been exploited to enable the history of the heavens to be investigated. Through the generosity of his main benefactor the Henry Draper Memorial had facilitated expansion of his team of assistants, the female half being ably led by Mina Fleming. Inevitably the continued success of HCO would be dependent on Pickering maintaining an efficient and focused team; unfortunately, his younger brother had other plans.

7.1. *A Problem in Peru*

William Pickering left for Arequipa in 1891 January on HCO's second Peru expedition. Solon Bailey's group departed in May, by which time William had already cabled his brother to send more funds. The demands grew more frequent as William overspent on land acquisition and house building.

By August the 0.33-m Boyden refractor had been erected near the Bache astrograph under superb conditions of seeing and transparency. To the increasing dismay of the HCO director the number of glass plates arriving from Arequipa reduced; it became apparent that William was mainly using the Boyden refractor as



Fig. 6. Discovery plate B2312 for the Horsehead Nebula, seen at left below the bright star Zeta Orionis (Alnitak) in Orion's Belt. It is probably the best-known object discovered by Williamina Fleming, but she is not usually credited with it. This plate is a 90-minute exposure with the Bache astrograph in 1888 February. (DASCH sample image)

a visual instrument for his planetary and lunar observations.

In 1891 October he received a directive from his older brother to begin the photographic programme. By 1892 June Edward Pickering had to inform him that he was to be recalled and would be replaced by Bailey; reluctantly Edward agreed to allow William to remain in Peru for the 1893 April solar eclipse.

William opted to use his remaining time observing the close Mars opposition of 1892 August. Further consternation in Cambridge arose when he then began cabling the New York Herald with a series of speculative ideas about Martian topography. In 1893 February Bailey's family group returned to Arequipa for a five-year term; HCO would at last have an efficiently operating southern hemisphere station.

7.2. *The Harvard Plate Store*

Storage of 30,000 glass plates in the West Wing of HCO had given its director many challenges. The wooden construction of the main building was a continual reminder to Pickering of the devastating fire of 1764 which had destroyed part of the original observa-

tory. Completion of a new fireproof three-storey brick building in 1893 March was therefore highly welcome.

Eight tons of glass plates were transferred using a rope and pulley system during a five-hour operation.⁷² Mina Fleming was now responsible for a facility costing \$15,000 (*c.* £270,000 today). In 1902 a brick extension would be added to facilitate further storage.⁷³ During her lifetime the Harvard collection would grow in size to 200,000 plates.⁷⁴

The relatively cramped working conditions for the women assistants had been apparent to Mrs Draper during her 1891 visit to HCO (Fig. 5). The key difficulty of retrieving speedily and safely a series of glass plates spanning nearly a decade would be significantly improved by the Plate Store.

In addition to her initial inspection of all incoming plates Mina often needed to trace back earlier examples for given regions of the sky. This had become a routine job for suspected long-period variable stars whose spectra often showed brighter hydrogen lines near maximum; she would select adjacent stars as comparison stars, determine their approximate positions, and then hunt for the suspect variable on older plates.⁷⁵

Inquiries were also arising from other astronomers. In 1892 September HCO received a request from Edward Singleton Holden (1846–1914), director of Lick Observatory, for confirmation of a new variable star in Aries; Mina soon found the star recorded on nine plates dating back to 1890 October.⁷⁶ Pickering's dream of capturing the history of the heavens was becoming a reality.

At the beginning of 1892 astronomers across the world were excited by the discovery of a bright new star in the winter sky by the Scottish amateur astronomer Thomas David Anderson (1853–1932). Nova Aurigae 1891 was the first to be studied by the spectrograph and Pickering reported HCO observations a fortnight after its announcement. Mina had examined Harvard plates from 1885 November, finding the first recorded image of it at 5th magnitude on a plate taken on 1891 December 10.⁷⁷

Spectra of the nova were photographed at Cambridge by both the 0.28-m Draper refractor and the 0.20-m Draper astrograph, with the latter recording low-dispersion spectra as the star faded. The possibility of finding fainter novae in other constellations within the HCO plate store would now be actively pursued at Cambridge.

During Antonia Maury's two-year absence the analysis of high-resolution spectrograms was another area tackled. Mina investigated first-magnitude stars, measuring their intensity at 20 different wavelengths; Pickering reported the findings in 1891 October.⁷⁸ In his 1891 *Annual Report* Pickering noted: 'An interesting discovery was made by Mrs. Fleming, that the bright lines in the spectrum of β Lyrae change their position in a manner somewhat like the doubling of the dark lines in β Aurigae.'⁷⁹

7.3. The Chicago Columbian Exposition in 1893

In the autumn of 1888 Mina met solar astronomer George Ellery Hale (1868–1938) who had begun working as a volunteer assistant at HCO while completing his MIT undergraduate studies. Hale tested a model spectroheliograph at Harvard and investigated the solar spectrum using a 0.30-m horizontal telescope; in 1890 improved instruments at Kenwood Astrophysical Observatory, Hale's private observatory in Chicago, facilitated his study of calcium in the spectra of prominences. Pickering supported Hale's early career in several ways. Through their liaison Hale gained respect for the tremendous discoveries being made by the Harvard women assistants, and became a lifelong friend of Mina Fleming.

In 1891 Hale visited astronomers across Europe to seek support for a new journal, *Astronomy and Astrophysics*, which ran to three volumes prior to the launch of *The Astrophysical Journal*.⁸⁰ Mina had begun writing papers under her own name in 1890 and was keen to send reports to Hale from her series on stars having peculiar spectra. In addition to her work on Nova Aurigae,

details of her latest discoveries of WR stars appeared regularly during 1892; by this time she had discovered 24 of the 37 known Wolf–Rayet stars.⁸¹

Hale used the pages of *AstAp* to promote the World Congress on Astronomy and Astrophysics to be held during the Columbian Exposition in Chicago in 1893 August.⁸² HCO was naturally expected to play a major role, and Mina was delegated two main tasks: preparation of an exhibition of 250 photographs from the Harvard Plate Store, and production of a paper on the role played by women computers at Harvard.⁸³

Although unable to attend the Chicago conference herself, this opportunity launched Mina into the world of international astronomy, enabling her to build valuable networks and guaranteeing her inclusion at similar gatherings for nearly two decades.

Her paper *A Field for Woman's Work in Astronomy* provides a valuable insight into her thoughts about her adopted country, the support she had received, and the work of her team:

The United States of America is a large country, with a large-hearted and liberal-minded people. Here they have made room for comers from all other countries, have welcomed them and have given a fair open field and equal advantages in pursuing their labors or studies, as the case may be. There is no other country in the world in which women, not as individuals, but as a class, have advanced so rapidly as in America, and there is no other country in which they enjoy the same unlimited freedom of action which affords them the opportunity to find their own level. In their studies they encounter very little narrow-mindedness or jealousy in their brother students or fellow workers in the same field of research, but in general they are treated with the greatest courtesy, encouragement and assistance being graciously accorded.

Labour honestly, conscientiously and steadily and recognition and success must crown your efforts in the end.

The measurements of about 40,000 stars are now being made by Miss Eva F. Leland. She is also engaged in the measurements of the brightness of the stars in clusters. Miss Louisa D. Wells and Miss Mabel C. Stevens have shown great skill and accuracy in making the identification of stars shown in the photographs, with those contained in existing catalogues ... micrometric measurements of the lines in the photographic spectra of the bright stars have been made by Miss Florence Cushman.

While we cannot maintain that in everything woman is man's equal, yet in many things her patience, perseverance and method make her his superior. Therefore, let us hope that in astronomy, which now affords a large field for woman's work and skill, she may, as has been the case in several other sciences, at least prove herself his equal.⁸⁴

Fig. 7a: Harvard College Observatory in 1887, looking southeast from the cottage used as a dark-room. In the foreground are: 0.32-m and 0.25-m photographic telescopes in the leftmost dome; the 0.20-m Bache astrograph in transit shed; 0.70-m $f/5$ reflector in the middle dome; 0.38-m reflector mounted in open; 0.28-m $f/14$ Clark photographic refractor in third dome, at right. From *First Annual Report of the Henry Draper Memorial project*, published in 1877.



One of the highlights of the Congress was the opening of the exhibit of the mounting for the Yerkes 1.0-m telescope, which had been erected in the huge Manufacturers and Liberal Arts Building, with accompanying talks by Hale, Clark, and Warner. Also attending the Congress was Dorothea Klumpke (1861–1942), an American working at the Paris Observatory, who delivered a paper on photographic charting of the sky.⁸⁵ At this time Dorothea was leading the Micrometer Service in Paris with a team of four female assistants. It is unfortunate that the two astronomers were unable to meet as they had much in common.

8. New stars and new challenges

In 1893 October Pickering announced Mina's discovery of a 7th-magnitude nova in the southern constellation of Norma, now known as IL Nor.⁸⁶ She had been examining spectra on a Bache plate taken that July in Arequipa and noticed the similarity of the bright hydrogen lines with those of Nova Aurigae 1892. Earlier plates to 14th magnitude showed nothing at this position.

Responding to a query from Jacobus Cornelius Kapteyn (1851–1922) over the exact position of the new star Pickering explained: 'Its exact position cannot readily be found at present since it appears only on a spectrum plate. Estimates by means of squares 1-mm on a side gave the position for 1875 ... a measure with the dividing engine gave a position.'⁸⁷

Encouraged by her success Mina resolved to use this spectral approach to seek more novae. In 1895 she was to be rewarded by three discoveries, one of which proved to be beyond the Milky Way (see Section 8.2).

8.1. The 0.60-m Bruce photographic telescope

Pickering's 1888 November request for \$50,000 for a photographic instrument with three times the aperture

of the Bache and Draper astrographs took five years to come to fruition. In 1889 June Catherine Wolfe Bruce (1816–1900) agreed to fund the 0.60-m $f/5.7$ instrument, which became known as the Bruce telescope. Its four-element objective using glass from Mantois in Paris was figured by the Clarks with two 0.60-m objective prisms. The design enabled fields 5° square to be photographed at a scale of 1 arc-minute per mm; at this scale, 1600 plates would cover the whole sky.

In 1893 November the astrograph was assembled in Cambridge for trials and in 1896 April Bailey had it operational in Arequipa. Pickering decided not to compete with the international *Carte du Ciel* and elected instead to use it for special investigations. Mina began receiving the large Bruce plates from Peru in 1896 September. By the end of 1899 over 4000 Bruce plates had been added to the Plate Store, some recording 400,000 stars to 16th magnitude.⁸⁸

8.2. HCO Circulars

As discoveries rapidly increased, Pickering launched the Harvard *Circulars* in 1895 October. In addition to her editorial responsibilities for the Observatory's *Annals* Mina now took over production of these important new publications.⁸⁹

Circular 1 announced the discovery of her second nova, now known as RS Car, which had appeared in Carina in 1895 April. A Bache plate of 60 minutes exposure taken in Arequipa had captured its spectrum, which was similar to those of Nova Aurigae and Nova Normae. Mina identified the bright lines by Greek letters for the first time: 'The hydrogen lines $H\beta$, $H\gamma$, $H\delta$, $H\epsilon$, and $H\zeta$ are bright, and the last four of these are accompanied by dark lines of slightly shorter wavelength.'⁹⁰ Further investigation showed evidence of spectral change as the nova faded.

Circular 4 in 1895 December announced two more nova discoveries, in Centaurus and Perseus.⁹¹ In 1934

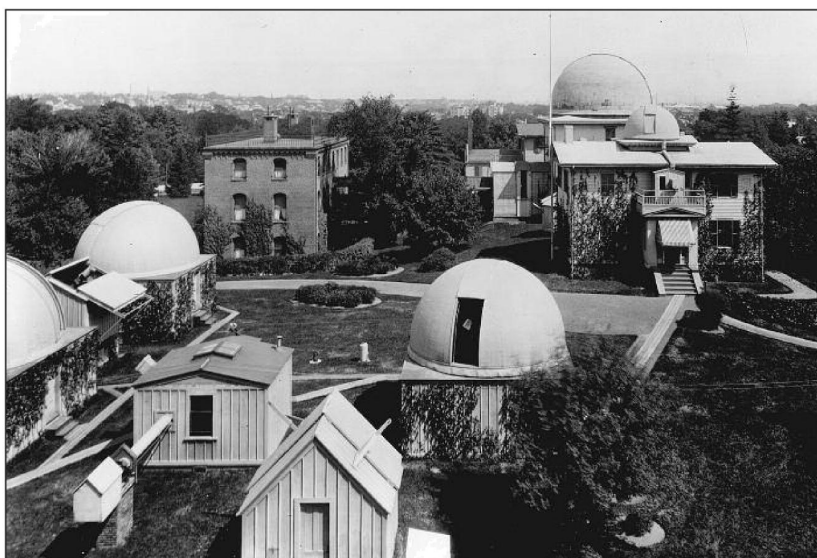


Fig. 7b: Harvard College Observatory c.1899 looking east. The Plate Store is in the three-storey brick building in the background at left; the 0.20-m Draper astrograph is in the runoff shed between the two domes at left; the 0.30-m horizontal photometer in left foreground was used by Hale for his first spectroheliograph. The large dome on the main building housed the 0.38-m 'great refractor' installed in 1847 which was for 20 years the largest telescope in the United States. (From 1915JRASC..9..203C)

the object in Centaurus was reclassified as SN 1895B. Located 25" from the nucleus of NGC 5253 it was the third extragalactic supernova discovered.⁹²

Circular 6 three months later listed 14 new variable stars of long period discovered by Mina who was now adept at spotting the bright hydrogen lines characteristically seen near maximum; she was also highly methodical in comparing spectral information on older plates.⁹⁴ To share her workload she delegated some variable star work to Eve Leland and Louisa Wells. Their first joint results appeared in *Circular 7* in 1896 June.⁹⁴

Mina's series titled *Stars having Peculiar Spectra* had become a regular HCO feature and *Circular 9* listed her continuation for mainly Type IV stars together with a gaseous nebula.⁹⁵ In discussing her WR discoveries of 1894 she had begun distinguishing between these two groups: 'The photographic spectra of faint gaseous nebulae and stars of the fifth type closely resemble each other and can only be distinguished by the wavelength of the principal bright line. In gaseous nebulae this line (5007) is of greater wavelength than H β while in stars of the fifth type the line (4688) is of shorter wavelength.'⁹⁶

In *Circular 11* the third spectroscopic binary discovered by HCO was announced. Solon Bailey had reviewed 52 plates of the star μ^1 Scorpii to calculate a period of 35 hours from the doubling of spectral lines. Mina Fleming would have found this frustrating as she had previously checked three earlier plates and noted 'lines double' on two of them; unfortunately pressure of work meant they were then overlooked.⁹⁷ However her disappointment proved brief as in the same month of 1896 August the twenty-fifth female assistant was appointed at HCO – a woman destined to become Mina's protégée.

8.3. Mentoring opportunities

Pickering had kept a watchful eye on potential college recruits to complement the skills of his staff. In the case of Henry Draper's niece Antonia Maury he had also

felt an obligation to the Draper family but became disappointed with her progress and absences.

Maury returned from Europe in 1895 December to begin her third period at Cambridge. This time her work focused on annotations for *Annals* volume XXVIII, Part I, *Spectra of Bright Stars Photographed with the 11-inch Draper Telescope as part of the Henry Draper Memorial*, published in 1897. Maury investigated the spectra of 681 bright stars north of declination -30° ; these were usually 60-minute exposures using up to four objective prisms which gave an 80-mm spectrum between He 3970 and H β 4861.^{98,99} Her study enabled her to develop a new spectral classification system.¹⁰⁰

Henrietta Swan Leavitt had graduated in 1892 from the Society for the Collegiate Instruction for Women, later renamed Radcliffe College. After taking additional astronomy courses she travelled abroad but unfortunately lost her hearing. She began volunteering at HCO in 1895. Initially she was involved in extending Mina's 1885 project on the photographic brightness of circumpolar stars. She then moved on to the photometry of variable stars, but a family crisis delayed her starting on payroll until 1902.

Annie Jump Cannon graduated from Wellesley College in 1884 where she was taught by physicist Sarah Whiting, who had close links with HCO. After her mother's death in 1894 Miss Cannon returned to Wellesley as an assistant to Whiting and enrolled in astronomy courses at Radcliffe. In 1907 she completed her MA degree at Wellesley.

Annie Cannon had a hearing disadvantage but was determined to accomplish something important with her life. Mina Fleming, who was six years older but had already achieved a highly successful career in astronomy, was an ideal role model.

Cannon began as a volunteer in 1896 February and unusually was allowed to observe variable stars in the evenings. In July she finished her Wellesley post and

became a permanent HCO assistant.¹⁰¹ *Circular 12* issued a few months later highlighted the existence of an unknown series of lines noted by Mina in the spectrum of the extremely hot star ζ Puppis. In *Circular 16* it was announced that Cannon had discovered the same lines in the spectrum of 29 CMa.¹⁰² They are now known to be due to ionized helium.

Fleming and Cannon struck up a close collaboration that brought a major advance to HCO spectral classification. Pickering found it easy to decide who should investigate the spectra of bright southern stars for the HDM.¹⁰³ Mina would now consolidate her mentoring role of Annie Cannon; she was training her successor.

9. Conferences, and a near-Earth asteroid

As Edward Pickering drafted the fiftieth HCO *Annual Report* at the end of 1895 he could reflect on many successes. His dream of managing observatories in both hemispheres and cultivating an excellent staff of committed astronomers was realized. He had used the 100-mm meridian photometer on 115 nights, making 73,448 measures; on one night he observed 322 stars during a six-hour period, using the same technique that he had developed in 1882.¹⁰⁴

Over the next 15 years he would average 130 evenings per year, including work with a new 0.30-m instrument, and make his one-millionth photometric setting in 1903 May.¹⁰⁵ This dedication meant that he began most days in the late morning; Mina's secretarial role ensuring the post and other matters demanding his scrutiny were already prepared.

The Yerkes Observatory dedication ceremony in 1897 October gave Hale the opportunity to convene the first American Conference of Astronomers and Astrophysicists, to which the HCO director and his wife were invited as special guests. Pickering delivered a summary of variable star work at Cambridge over the previous 5 years, explaining that 'the spectra of a large part of this class of [long period] variables are of the third type, and when near maximum the hydrogen lines are bright.'¹⁰⁶ Pickering praised Mina's discoveries of 80 variables; these included 26 in 1895 and 30 in 1896 which she had published in the *Astrophysical Journal* and HCO *Circulars* respectively.¹⁰⁷ At the conclusion of the conference Hale announced that the next venue would be at Cambridge in 1898.

Mina was also now being acknowledged as co-author of some Harvard *Annals*. In Volume XXVI, Part II, *Miscellaneous Investigations of the Henry Draper Memorial*, she is credited as 'M. Fleming, Assistant'.¹⁰⁸ Her classification of a thousand stars across seven open clusters utilized plates from both the Bache and Draper astrographs. For the Pleiades she investigated 91 stars finding 65% class A, while in contrast a similar number of stars in Praesepe had only 31% class A.¹⁰⁹

9.1. Second Conference of Astronomers and Astrophysicists

The second annual conference of astronomers and astrophysicists was held at HCO in 1898 August, attended by 92 delegates including 17 women.¹¹⁰ Mina played a leading role in organizing events.

Among the 24 papers presented was Mina's contribution on *Stars of the fifth type in the Magellanic Clouds*.¹¹¹ Pickering presented her paper and in conclusion added: 'Mrs Fleming had omitted to mention that of the 79 stars nearly all had been discovered by herself, whereupon Mrs Fleming was compelled by a spontaneous burst of applause to come forward and supplement the paper by responding to questions elicited by it.'¹¹² Mina's discovery of six WR stars in the Large Magellanic Cloud had been announced in *Circular 19* in 1897 September from an examination of plates taken by the 0.60-m Bruce astrograph.¹¹³

The third conference, held at Yerkes Observatory in 1899 September, was also the inaugural meeting of the newly constituted Astronomical and Astrophysical Society of America (A&ASA); this organization was eventually to grow into the American Astronomical Society. Simon Newcomb (1835–1909) was elected President and Pickering delivered a paper on the *Revised Harvard Photometry*. Annual meetings continued at venues in New York, Washington (twice), St Louis, and Philadelphia, with Pickering in regular attendance. Mina's role within America's leading society began in 1905 when Pickering was elected President.

9.2. The hunt for Eros

One week before the Cambridge conference Carl Gustav Witt (1866–1946), director of the Urania Observatory in Berlin, discovered an indistinct 0.4-mm line on a 2-hour exposure; he soon realized it was a fast-moving asteroid near aphelion.¹¹⁴ Asteroid 433, later to be named Eros, had a strange elliptical orbit which would bring it closer to Earth than any similar object except the Moon.

Circular 34 described Wendell's photometric measurements of the asteroid made through the 0.38-m refractor plus Mina's analysis of its photographic brightness on plates taken by the 0.20-m Draper astrograph; both of them found the minor planet to be 12th magnitude.¹¹⁵

In November HCO received a request to find Witt's object within its Plate Store, as earlier positions would enable its orbit to be more accurately determined. To aid the search, Seth Carlo Chandler (1846–1913) produced an approximate ephemeris but with a large degree of uncertainty. Mina eventually examined over 1300 square degrees on plates from three astrographs, representing 3% of the entire heavens.

Twenty-one plates were found and labeled with the asteroid and comparison stars used to locate its position.¹¹⁶ *Circular 36* in 1898 December described her work as 'especially laborious and fatiguing to the eyes'.¹¹⁷ It involved superposing two plates of the same region

taken with the same instrument and checking for a single faint image. Success with plates taken in 1896 April and June enabled Chandler to improve the ephemeris, from which Mina located plates for 1893–4.¹¹⁸ Mina's reward for this mammoth task was to be taken off HCO payroll in 1899 and be made an employee of Harvard Corporation under a new title; her astronomical career was now officially approved.¹¹⁹

10. Curator of Astronomical Photographs

As the 19th century drew to a close Mina's discoveries continued steadily. A new remarkable object was announced in 1897 November: a Bache spectrum plate taken in June in Arequipa had included the spectrum of a bright meteor, with six bright lines measured by Mina.¹²⁰

Pickering decided to make a special effort to obtain meteor trails and spectra during the annual November Leonid shower. HCO *Circulars* 31, 35, and 40 describe the methods adopted. Observers were stationed both at both Cambridge and 20 km south at the Blue Hill Meteorological Observatory.

In the first year 91 and 47 meteors were recorded respectively.¹²¹ The following year, 1898, 800 meteors

Fig. 8. Mina Fleming in the enlarged Harvard Plate Store. She was responsible for the Store from 1893 until her death in 1911. During this time the number of glass plates increased to 200,000 enabling the 'history of the heavens' to be investigated for the first time. (UAV 630.271 (388) Harvard University Archives)



were recorded at Cambridge by 30 observers. Five photographic doublets covered the region within 30° of the radiant. Parallax measures were obtained using a second station to the north but no spectra were obtained.¹²²

Pickering then sanctioned two wide-angle cameras for Cambridge and Blue Hill to regularly patrol the heavens. Three plates were to be taken every night with the aim of determining the altitude, radiant point, velocity, and spectrum of one-third of all bright meteors visible.¹²³

Circular 21 included the observation that β Lupi might be a spectroscopic binary; Mina was keen to add such an object to her portfolio, but further photographs proved inconclusive.¹²⁴ In *Circular 24* she was on safer ground, providing details of recent variable star discoveries, including those made by her assistants Louisa Wells and Eve Leland. It was now common practice at HCO to photograph many of these stars monthly and combine results with up to 100 library plates to deduce any light curves.¹²⁵

Pickering was also keen to discover short-period variables photographically. Using a Cooke anastigmatic 26-mm f/13 astrograph with a 20×30-cm plate, eight 10-minute exposures were obtained over a 7-hour period for a region 33° square. This method was designed to discover any variable star with a period shorter than 14 hours, as both a maxima and minima would be recorded; Pickering estimated that the entire sky could be covered in just 40 plates to 9th magnitude and that amplitudes of 0.5 magnitude would be measurable.¹²⁶

Mina's series of papers under the name *Stars having Peculiar Spectra* continued for the Draper Memorial project in 1898 June. In the November issue of *Aph* she explained further her classification of the spectra of long-period variables, for which around 100 new examples with bright hydrogen lines had been found.¹²⁸

In 1899 March, after a three-year gap, she found her fifth and brightest nova, in Sagittarius, now known as V1059 Sagittarii. *Circular 42* announced details of the new star which had been photographed in Arequipa in 1898 March at magnitude 4.7.¹²⁹ Pickering duly noted that of the 15 novae discovered in the last four centuries Mina had discovered one-third of them. Her tally increased to six in 1900 July with 7th-magnitude Nova Aquilae (V606 Aql), discovered from the existence of seven bright lines on plates taken the previous year.¹³⁰

A 1900 spring visit to Europe by Edward and Lizzie Pickering included the Paris Exposition, for which Mina prepared some 400 plates from the Harvard Plate Store.¹³¹ Later that year Pickering was awarded his second Gold Medal from the RAS 'for his researches on variable stars and his work in astronomical photography'. In his address on making the presentation, RAS President Edward Ball Knobel (1841–1930) noted 'the important part of the work undertaken by lady assistants, one of whom – Mrs. Fleming – is entitled to our

gratitude, as from her minute and accurate examination of the photographs she has been able to announce some of the most interesting discoveries in variable stars and stars with peculiar spectra that have been recorded.¹³²

10.1. *Mina's 1900 Journal*

A revealing insight into Mina's thoughts aged 42 is provided by the Harvard University 'Chest of 1900' time-capsule project. At this time her son was 20 and Annie Cannon was lodging with the pair at 273 Upland Road, Cambridge.¹³³

March 1, 1900: In the Astrophotographic building of the Observatory 12 women including myself are engaged in the care of the photographs; identification, examination and measurement of them; reduction of these measurements and preparation of results for the printer ... My home life is necessarily different from that of other officers of the University since all housekeeping cares rest on me ... My son Edward, now a junior in the Mass. Inst. of Technology, knows little or nothing of the value of money and, therefore, has the idea but that everything should be forthcoming on demand. The first part of this morning at the Observatory was devoted to the revision of Miss Cannon's work on the classification of the bright southern stars, which is now in preparation for the printer ... several pages of the remarks on the individual stars were read, criticized, corrected or questioned.

March 3: Another full day at the Observatory from 9[a.m.] to 6 [p.m.]. Part of the morning I spent with Miss Cannon, discussing the remarks on her classification, and explaining the reasons why we had changed one thing and questioned another ... Looking after the numerous pieces of routine work which have to be kept progressing, searching for

confirmation of objects discovered elsewhere, attending to scientific correspondence, getting material in form for publication, etc., has consumed so much of my time during the past few years that little is left for the particular investigations in which I am especially interested. The Director, however, says that my time employed in the above work is of more value to the Observatory so I have delegated my measures of variables, etc., to Miss Leland and Miss Breslin.

March 4 [Sunday]: This is my day of rest and retirement so far as Observatory work is concerned.

March 5: If one could only go on and on with original work looking for new stars, variables, classifying spectra and studying their peculiarities and changes life would be a most beautiful dream ... I am more than contented to have such excellent opportunities for work in so many directions, and proud to be considered of any assistance to such a thoroughly capable scientific man as our Director.

March 12: I had some conversation with the Director regarding women's salaries. He seems to think that no work is too much or too hard for me. But let me raise the question of salary and I am immediately told that I receive an excellent salary as women's salaries stand. Sometimes I feel tempted to give up and let him try some one else, or some of the men, in order to have him find out what he is getting for \$1500 a year from me, compared with \$2500 from some of the other assistants. Does he ever think that I have a home to keep and a family to take care of as well as the men?

At this time Mina was receiving weekly physiotherapy for her right arm. Repetitive strain injury affected some female assistants and the continuous retrieval of glass plates for scrutiny involved significant physical labour.



Fig. 9: HCO staff aboard C. S. Minia in 1900 May, en route for the solar eclipse in Georgia. Front row, from left: Louisa Wells, Mabel Gill, Mina Fleming (holding Gill's hand), Mabel Stevens, Evelyn Leland. Middle row: Captain William De Carteret, Edward Fleming (Mina's son), Edith Gill, Florence Cushman (partly obscured behind Mina), Imogen Eddy, and Ida Woods. Back row: unknown man and ship's officer, probably James Adams. The Minia, a cable repair ship, found unwanted fame 12 years later when she was one of the vessels chartered to recover bodies from the Titanic disaster. (UAV 630.271 (173), Harvard University Archives)

Mina's journal reflections on her salary warrant further scrutiny. Lafortune has reviewed HCO payroll records, which had been subject to an 80-year blackout.¹³⁴ This analysis reveals Mina was on payroll from 1881 and received an increase in salary to \$83 per month (\$1000 a year, *c.* £18,000 today) between 1891 and 1896 November. Between 1896 December and 1898 October she received \$125 per month (\$1500 a year, *c.* £27,000 today); after this time she was paid by Harvard Corporation.

Her first pay rise coincided with the publication of two volumes of the *Annals* for the *Draper Catalogue*; curiously it began two years after she took responsibility for recruiting female assistants (in 1888) so presumably she was serving a probationary period to prove her management skills.

The more significant increase in 1896 December, which continued until at least 1900 April according to her journal, followed her successful organization of the Harvard conference of astronomers and astrophysicists and significant contributions to the HCO *Circulars*; it coincided with her new position as Curator of Astronomical Photographs. Until 1911 Solon Bailey received \$1000 per year, so Mina's reference to 'other (male) assistants' probably related to Wendell and Searle who both served long careers at HCO.

10.2. *A trip to Georgia*

Edward Pickering returned to Cambridge just before two expeditions departed to view the total solar eclipse of 1900 May from Georgia. The official party was led by William Pickering who hoped to find an intra-Mercurial planet.¹³⁵ The HCO staff excursion (Fig. 9) accompanied small groups from MIT and Blue Hill Observatory who chose Washington, Georgia, for their location.

For Mina and her son this was an opportunity to view a solar eclipse near solar minimum. Totality lasted 90 seconds with equatorial streamers observed to 3.5 solar diameters. A 75-mm f/15 camera was used by the MIT observers. Just prior to the eclipse Mrs Draper decided also to view the eclipse and persuaded Edward and Lizzie Pickering to accompany her as guests. Before their departure from Georgia the whole group enjoyed 'afternoon teas and a farewell barbecue'.¹³⁶

11. Mina Fleming and Annie Cannon

By 1901 there were 45 volumes of HCO *Annals* completed, of which Mina had worked on 39. Volume XXVIII, Part II, was *Spectra of Bright Southern Stars* by Annie Cannon and included her classification of 1122 stars from analysis of 5961 plates photographed at Arequipa with the Boyden telescope. The 0.33-m refractor was used with up to three objective prisms, producing measurable spectra from H ϵ to H β of up to 74 mm in 60-minute exposures.

Cannon used a 50-mm eyepiece to examine each plate and modified the spectral classification first developed by Fleming for the Draper Catalogue.¹³⁷ The higher dispersion allowed her to introduce decimal subdivisions for spectral types; she also reordered some letters, which would later result in the famous O, B, A, F, G, K, M, R, N, S sequence.

From Mina's 1900 Journal it is clear that Annie Cannon was lodging with her. Whether this arrangement began when Cannon started at HCO in 1896 is unknown; however it is probable since Cannon regularly observed variable stars from HCO in the evenings and Mina lived close to the Observatory. The author has transcribed Cannon's diary for 1905 and found that she was living at 52 Concord Avenue between June and October.¹³⁸

Mina's Journal makes it clear that the two women occasionally worked together at home in the evenings on HCO matters. Hence it seems probable that some of the credit for Cannon's later success on spectral classification can be traced to the role of her mentor during the first 15 years of her career at HCO.

11.1. *The discoveries continue*

Circular 54 issued in 1901 January detailed another batch of variable stars, 53 of them discovered by Mina.¹³⁹ Among them was a star with a range of 0.8 magnitude and a period of just over half a day; this we now know as RR Lyrae.¹⁴⁰ Mina's 1901 summer *Circular* summarized her latest group of *Stars having Peculiar Spectra* in which a large number of gaseous nebulae and Type V stars were listed.¹⁴¹

The year 1902 was celebrated as the 25th anniversary of Pickering's directorship. An anonymous gift of \$20,000 (*c.* £360,000 today) was partly used for the Plate Store extension. In May discovery of a new Algol variable in Cygnus was announced, found by Mina while searching for an image of Comet Brooks; some 400 plates were inspected to construct a light curve with a period of 31.3 days, the longest of any then known.¹⁴² It is now known as UZ Cygni.

In August Miss Leavitt returned to HCO, becoming the thirty-first female assistant. She was assigned to study variable stars on the Bruce plates from Arequipa. Her work on Cepheid variables within the Large and Small Magellanic Clouds would later be internationally acclaimed.

Annie Cannon had begun collating variable stars in 1900 September and a summary of her work was published in the Harvard *Annals* in 1903 as *A Provisional Catalogue of Variable Stars*.¹⁴³ This volume listed 1227 stars, of which HCO staff had discovered 694; Bailey was credited with 509 variables within globular clusters while Fleming's total was 166.

In 1903 March the English astronomer Herbert Hall Turner (1861–1930) discovered a possible nova in Gemini. *Circular 70* described the follow-up investigation by Mina and Eve Leland; they found it had been

magnitude 5 at brightest and its spectrum revealed six bright lines.¹⁴⁴

Pickering's 1903 *Annual Report* noted: 'Owing to the pressure of other work during the daytime Mrs. Fleming has not been able for some time to continue the classification of the spectra for the Southern Draper Catalogue. Suitable arrangements have accordingly been made so that she is now doing this work at her home in the evening. In this way she has classified the spectra and measured the light of 3,506 stars. These stars are all south of declination -60° .'¹⁴⁵

The HCO Plate Store had passed the 150,000 mark by 1903. Pickering explained: 'On the average, photographs are included of every portion of the sky, taken on about two hundred nights, from 1889 to the present time, and showing stars as faint as the eleventh magnitude. A nearly continuous history of the sky, such as does not exist elsewhere, is thus furnished.'¹⁴⁶

A Carnegie Institution grant of \$2500 (*c.* £45,000 today) had improved HCO's capacity to mine this mass of plates. Mina had successfully appointed her sister, Mrs Johanna Crichton Stevens Mackie (1860–1943), and she was soon joined by their niece, Ida May Stevens, whom Mina had nurtured as she grew up in Cambridge.¹⁴⁷ These two additions to Mina's team proved to be replacements for Anna Winlock and Imogen Eddy, who both died in 1904 after 28 and 15 years service respectively to Harvard College Observatory.

In 1904 March Mina noted the variable star RS Ophiuchi as a potential nova based on its spectrum of the third type with bright hydrogen lines and two more bright lines similar to γ Velorum.¹⁴⁸ This star, typically of 11th magnitude, was found to have brightened to at least magnitude 7.7 in 1898 June. In 1905 May Pickering approved its reclassification from a variable star to 'Nova Ophiuchi, No. 3'.^{149,150}

11.2. *Pickering's presidency of the A&ASA*

In 1905 September Mina discovered her eighth nova, and her second in Aquila.¹⁵¹ But it was events at the end of December that proved more important. At the seventh meeting of the Astronomical and Astrophysical Society of America, held at Columbia University, New York, Edward Pickering was elected the second President, a role in which he continued until 1919. For Mina Fleming and Annie Cannon it proved an opportunity to attend an evening reception at the Madison Avenue home of Mrs Draper. They also presented papers on *Peculiar Spectra* and *Variable star light-curves*.¹⁵² It is unclear how much additional work Mina was delegated following Pickering's election.

In 1906 May Mina received international recognition when she was made an Honorary Member of the Royal Astronomical Society, only the fifth woman to receive this accolade.¹⁵³ Praise by her homeland was undoubtedly pleasing but Mina was probably more humbled by being appointed an Honorary Fellow of Wellesley College that same year; although not a grad-

uate, Mina supported the philosophy of this leading women's college, which had supplied Harvard College Observatory with such an excellent trainee in Annie Cannon.¹⁵⁴

The same year proved busy for recruitment. Continuing low pay might have influenced some experienced computers to resign, but Mina replaced them with four new ladies who would all give excellent service: Grace Brooks, Alta Carpenter, Mollie O'Reilly, and Arville Walker, all of whom started at Harvard in 1906.

Mina's *Circulars* included her usual batch of *Stars having Peculiar Spectra* and variables, including another Algol-type.¹⁵⁵ She had now discovered 50 (of the 63 known) Wolf-Rayet stars. While examining plate A6911, a 4-hour exposure taken by the 0.60-m Bruce astrograph, Mina identified a large triangular wisp of nebulosity near the star 52 Cygni. Today this is known as 'Pickering's Triangle' or, more accurately, 'Fleming's Triangular Wisp', part of the Veil Nebula supernova remnant.¹⁵⁶

In 1906 August Lizzie Pickering, Edward's wife of 34 years, died after a long illness,¹⁵⁷ but he carried on with his usual energy. Early the following year in *Circular 123* Pickering summarized the type of requests they dealt with, neatly explaining the varied roles of Mina and her team: 'For instance, evidence of the previous existence of a new star; of a star now missing; the position of an asteroid; the magnitude at minimum of a faint variable; early position of a faint star suspected of proper motion.'¹⁵⁸

A serious fire in 1907 March threatened to consume the director's residence. While Pickering tackled a burning sofa, Mina used her extinguisher on the flames licking a large casement window and ceiling cornice. Together with other members of the HCO fire-fighting team the situation was under control by the time the city brigade arrived.¹⁵⁹

In 1907 October Mina tabulated a list of red stars in the vicinity of Nova Velorum, which had been discovered the previous year by Henrietta Leavitt.¹⁶⁰ At this time Miss Leavitt was contributing to Mina's previous project on developing a standard North Polar Sequence, while Annie Cannon focused on identifying variables among the two million stars imaged on the Harvard Map of the Sky.¹⁶¹ Three more female assistants were appointed, including Margaret Harwood (1885–1979) who worked at HCO for six months a year for five years.¹⁶²

Publication of HCO *Annals* XLVII Part I, *A Photographic Study of Variable Stars*, proved a major milestone for Mina in 1907.¹⁶³ This volume contained sequences of comparison stars for each of 222 variables discovered by her or under her direction on the Henry Draper Memorial plates. Most of these variables were identified from their Type III spectra, displaying bright hydrogen lines.¹⁶⁴ Another milestone, this one personal rather than professional, was that she became an American citizen in September that year.¹⁶⁵

11.3. *The Bruce Medal*

In 1908 Edward Pickering was awarded the Bruce Medal of the Astronomical Society of the Pacific for his work on photometry, spectroscopy, and photography; he was the seventh recipient since 1898. Pickering had proposed Mina for the award in 1900, adding the following year: ‘I cannot do better than repeat my recommendation of last year that “in view of the important part taken by women in American Astronomy, and since the Bruce Medal was established by a woman [Catherine Wolfe Bruce, who also funded the Harvard astrograph], I recommend the woman who has made the most important astronomical discoveries, Mrs. W. Fleming.’”

In 1905 he strengthened his nomination: ‘Mrs. W. P. Fleming, for her discoveries and continuing researches in stellar spectroscopy, extending over the last 24 years. She has discovered nearly all of the Novae, stars of the 5th light and stars having hydrogen lines bright which have been found during the last 20 years. See also her work published in Harvard *Annals* 26, 27, 50, in Harvard *Circulars* ... and publishing and editing many other volumes.’¹⁶⁶ Pickering’s nominations were to no avail and it would not be until 1982 that a female astronomer, Margaret Burbidge, finally received this international honour.

Advances in printing technology significantly reduced production times of the *Annals* after 1907. As Pickering explained to David Gill: ‘We have just introduced a monotype, a machine by which one typewriter can do the job of four compositors. The energies of the entire Observatory are being exhausted in keeping this monster supplied with copy.’¹⁶⁷

Volume L of the *Annals*, published in 1908, was the *Revised Harvard Photometry*, a major catalogue of positions, photometric magnitudes, and spectra for 9110 stars to magnitude 6.5, the forerunner of the *Bright Star*

Catalogue.¹⁶⁸ Pickering noted in the Preface that Mrs Fleming ‘has devoted a large part of her time to the supervision of the preparation for publication of the present Volume’.

Her other main publication of 1908 was *Circular 145* in which she proposed a sixth type of stellar spectra, listing 51 examples of stars showing dark absorption bands.¹⁶⁹ This suggestion had previously been presented at the ninth meeting of the A&ASA held in August at Lake Erie, Ohio, which Mina attended with Pickering.¹⁷⁰

At the tenth meeting of the A&ASA a year later at Yerkes Observatory, HCO representation included the impressive line-up of Fleming, Leavitt, and Cannon who delivered papers on meteor spectra, standard photographic magnitudes, and variable stars respectively.¹⁷¹ Mina continued her August trip westwards to visit her son in Salt Lake City, where he was now working as a metallurgist, and they journeyed together to Los Angeles.¹⁷²

12. New theories of stellar evolution

In 1909 September Henry Norris Russell (1877–1957) contacted Pickering about his hypothesis for two types of red stars. In 1908 July Ejnar Hertzsprung (1873–1967) had made a similar distinction between nearby red dwarf stars and more distant giant stars. He regretted the omission of Maury’s ‘c’ characteristic from Volume L of the *Harvard Annals*; his combined work with Russell would result in a new theory of stellar evolution, including the H–R Diagram, in 1913.¹⁷³ Mina’s initial contribution to this debate appeared in *Circular 149* in 1909 March. A two-hour Bache exposure of a region in Sagittarius had revealed a large number of red stars with peculiar spectra, while a shorter exposure of 69 minutes recorded very few red stars.

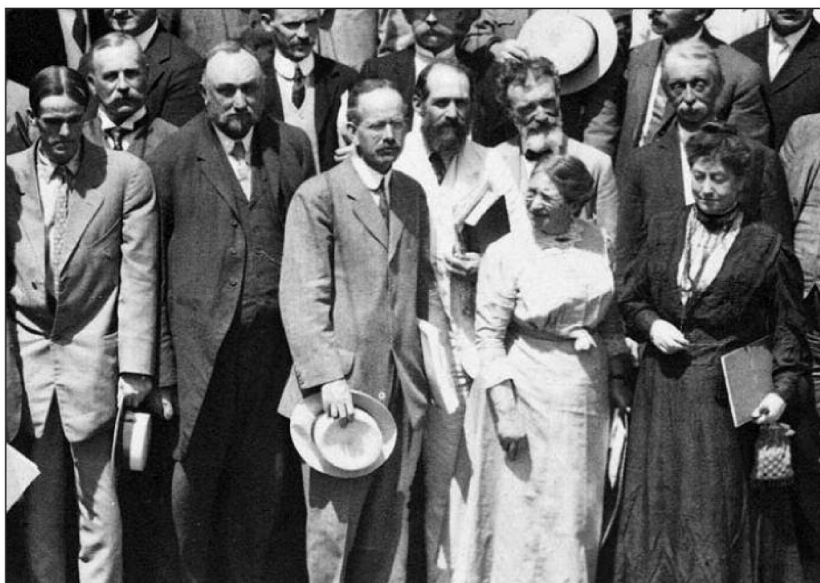


Fig 10: The 1910 meeting of the International Union for Cooperation in Solar Research, better known as the Solar Union, was held at Mount Wilson. Among the attendees were, in the front row, Walter S. Adams, Edward C. Pickering, George E. Hale, Mrs Elise Kapteyn, and Williamina Fleming, with Jacobus Kapteyn behind Mina. (Kapteyn Astronomical Institute)

12.1. *The first white dwarf: 40 Eridani B*

In 1910 Mina made an important observation regarding the triple star Omicron² Eridani, more usually known as 40 Eridani. She classified the spectral types of the three components as K, A, and G, raising an intriguing puzzle: how could the ninth-magnitude companion to a fourth-magnitude primary have a spectral type, A, associated with some of the hottest stars known? Pickering commented sagely: 'It is just such discrepancies which lead to the increase of our knowledge.'¹⁷⁴

At that time Russell was visiting HCO prior to the 1910 August meeting of the A&ASA in Cambridge. His work on the parallax of nearby stars had extended to noting their spectral type from the Harvard plates. Russell doubted the reliability of Mina's 'discrepancy' but included it in his graph of spectral types plotted against absolute magnitudes. Hertzsprung also agreed with Russell that faint white stars were unlikely.

The breakthrough came at the end of 1914 when Walter Sydney Adams (1876–1956) succeeded, after a two-year campaign with the 1.5-m reflector at Mount Wilson, in obtaining a spectrum for Sirius B, which he classified as A0. This agreed with Mina's result and showed there were at least two small, dense, hot stars. A third example was found at Mount Wilson in 1917 by Adriaan van Maanen (1884–1946).¹⁷⁵ Such stars are now known as white dwarfs, the exposed cores of stars such as the Sun that have lost their outer layers.

12.2. *The 1910 meetings of astronomers*

Planning for the eleventh meeting of the A&ASA at HCO in 1910 August occupied many months. The three-day conference involved five sessions, 48 papers, and over 100 delegates, 15 of them female (Fig 10). Excursions to the Whitin Observatory at Wellesley College and the Blue Hill Meteorological Observatory were organized as well as to the astronomical laboratory at Harvard University. Immediately afterwards most astronomers departed from Boston for the long journey to Pasadena to attend the fourth meeting of the International Union for Cooperation in Solar Research, also known more simply as the Solar Union or ISU, on August 31–September 2.¹⁷⁶

This meeting was held at Mount Wilson Observatory where Hale had established the 1.5-m reflector and two solar towers. Eighty delegates attended, including 37 from Europe; in all 13 countries and 50 different observatories were represented, making the event the largest ever gathering of astronomers in the world. For Williamina Fleming the meeting marked the pinnacle of her acceptance on the world astronomical stage. The journey from Boston to Pasadena occupied eight days with visits to Niagara Falls, Chicago, the Lowell Observatory in Flagstaff, and two days at the Grand Canyon before a crossing of the Mojave Desert to reach their destination.¹⁷⁷

At Pasadena delegates viewed the laboratories and workshops including Hale's spectroheliograph design

for the 45-m Tower Telescope and the 2.5-m glass blank for the Hooker Telescope. An afternoon garden party at the Hales' home at Hermosa Vista proved an enjoyable distraction from concerns over the following day's ascent of Mount Wilson. An average gradient of 1:10 up dusty, narrow tracks occupied eight hours, with most delegates opting for mule-drawn carriages.

Mount Wilson hotel accommodated half of the delegates with the remainder under canvas for four nights. Pickering and Fleming were the HCO delegates, the director being housed in a cottage while Mina enjoyed meeting six female assistants from Mount Wilson's staff. At the end of proceedings most delegates travelled north to visit Lick Observatory. Mina opted to make her second journey to Salt Lake City to visit her son Edward; it would prove to be their last meeting.

Three outcomes of the Solar Union meeting impacted directly on HCO. First, delegates agreed to expand the remit of the Union to include stellar spectra. Second, Pickering secured global agreement on his plan for Standard Photographic Magnitudes. And third, the Harvard system of spectral classification, fundamentally the six classes designated B, A, F, G, K and M, received widespread approval. Pickering had now received the necessary global endorsement for his lifetime's work.¹⁷⁸

Three years later, in 1913 April at Bonn, the fifth Solar Union meeting universally adopted the Harvard spectral classification system; Pickering and Annie Cannon attended this meeting. Nine years later, in 1922 May at Rome, the newly created IAU formally approved the Harvard system.

12.3. *Final months*

Shortly after the Solar Union meeting, while still with her son in Salt Lake City, Mina learnt of the death of her mother in Cambridge.¹⁷⁹ This necessitated her immediate return to the north-east, but by the time Pickering returned in mid-September HCO routines were back to normal. One of his first tasks was to confirm Mina's latest two discoveries.

Nova Sagittarii No. 2 was her ninth nova, discovered from its faint spectrum on a Bache plate taken in March at magnitude 7.8.¹⁸⁰ Nova Arae was her tenth nova, discovered in a similar way on an April plate at magnitude 6.0.¹⁸¹ Pickering proudly announced the ongoing success of his team: 'Of the 16 new stars found during the last 25 years, 13 have been found at this Observatory, one by Miss A. J. Cannon, two by Miss H. S. Leavitt from photographic charts and 10 by Mrs. Fleming from the Draper Memorial photographs.'

Discussions at the final session of the Solar Union meeting had resulted in formation of a committee to recommend a stellar spectral classification system. Written responses were invited from leading astronomers, with 28 received from 17 different observatories, the majority backing the Draper system.¹⁸²

In November Pickering voiced his expectation that stellar evolution theories would soon be forthcoming

and that the proven Draper system could support these. Antonia Maury conveyed a similar wish for an evolutionary scheme with retention of the observations of line width and sharpness visible in high-dispersion spectrograms.

In 1911 January Mina expressed the hope that new technology might improve the definition of fainter spectra. At this stage she had divided class M into four subclasses with one of these further divided into eleven groups. By February Annie Cannon had studied 4300 photographic spectra. Her response promoted the O, B, A, F, G, K, M system with decimal subdivisions, but also included the need to incorporate results from slit spectrographs as well as objective prisms.¹⁸³

Pickering was now 64 years old and actively seeking to delegate some of his responsibilities to Solon Bailey, whom he hoped would soon succeed him as director of HCO. Bailey had led the HCO expedition to South Africa in 1909, finding an excellent observing site near Bloemfontein which would eventually become the southern hemisphere replacement for Arequipa in 1927. However Pickering was struggling to raise sufficient finance at this time and having to dismiss some male assistants; interest rates had fallen and even Mrs Draper had to halve her monthly contributions to \$400 per month (c.£7200 today) after 20 years of generous support.

Mina concentrated on the completion of *Annals* Volume LVI which included eight sections relating to stellar spectra. Part VI was her main focus, *Stars having Peculiar Spectra*.¹⁸⁴ Published in 1912, it effectively summarized in 60 pages her work for the Henry Draper Memorial over nearly three decades. Her final *Circular* appeared four months after her death from pneumonia in Boston Hospital on 1911 May 21. Typically it covered more *Stars having Peculiar Spectra* and discoveries of variable stars.¹⁸⁵

13. Tributes to Mina Fleming

In his 1911 *Annual Report* Edward Pickering marked the passing of his close colleague:

The Observatory has suffered a severe loss by the death, on May 21, 1911, of Williamina Paton Fleming, Curator of Astronomical Photographs. She was an Honorary Member of the Royal Astronomical Society, an Honorary Fellow of Wellesley College, and last winter received the gold medal of the Mexican Society of Sciences. Mrs. Fleming's record as a discoverer of new stars, of stars of the fifth type, and of other objects having peculiar spectra, was unequalled. Her gifts as an administrative officer, especially in the preparation of the *Annals*, although seriously interfering with her scientific work, were of the greatest value to the Observatory.¹⁸⁶

Pickering believed Mina's chief gifts were executive and administrative. As he recalled: 'A gift of order is much different from a gift of administration. The former

helps the latter. Mrs. Fleming had both. She was very methodical and possessed an extraordinary memory, which was especially manifest in her preparation of the observatory records.'¹⁸⁷

Her obituary in the *Monthly Notices* of the RAS by Herbert Hall Turner noted: 'Within the last year or two more than one serious operation had been necessary ... It would be unjust not to remember that she left her heavy daily labours at the observatory to undertake on her return home those household cares of which a man usually expects to be relieved. She was fully equal to the double task.' Turner had great admiration for Mina Fleming, especially her work on variable stars: 'Many astronomers are deservedly proud to have discovered one variable, and content to leave the arrangements for its observation to others: the discovery of 222, and the care for their future on this scale, is an achievement bordering on the marvellous.'¹⁸⁸

Annie Cannon produced the most detailed obituary, which included this tribute:

Gifted with great keenness of vision and a clear and logical mind ... she never doubted the validity of the photographic evidence. Her industry was combined with great courage and independence ... her power of grasping facts quickly and clearly was useful in final readings and corrections of [*Annals*] copy and proof ... her great natural vitality and courageous spirit had sustained her through trying illnesses ... Mrs. Fleming was possessed of an extremely magnetic personality and an attractive countenance, enlivened by remarkably bright eyes [very dark brown] ... fond of people and excitement, there was no more enthusiastic spectator in the stadium for the football games, no more ardent champion of the Harvard eleven ... she was never too tired to welcome her friends at her home or at the observatory ... her cheery greeting with its charming Scotch accent, will long be remembered by even the most casual visitors to the Harvard College Observatory.¹⁸⁹

Local media in Cambridge recorded: 'No other woman astronomer has so brilliant a line of achievements to her record ... she seemed to read the heavens as an open book ... editing more than 20 quarto volumes of astronomical publications ... the intricate maze of computations which could keep more than a dozen women computers steadily busy.'¹⁹⁰

Grace Thompson described Mina as 'the most efficient woman investigator ... manifesting a very genius for the task of organisation'.¹⁹¹ Always heeding the advice and approval of the director, 'her discerning scientific judgement suggested many of the most important and interesting investigations undertaken, and then aided in planning and carrying them out with an unerring precision.'¹⁹² Mina's creative tastes were also reviewed:

She might have supported herself by needlework, millinery, dressmaking ... she delighted in doing

bits of sewing ... Mrs. Fleming's dolls always sold readily, those in full Highland costume being especially popular ... a Christmas tree for the children of families connected with the observatory work of Arequipa Station in Peru ... everyone helped enthusiastically ... Mrs. Fleming insisted they should be astronomical dolls ... Vega, Castor, Pollux ... quite an astronomical sensation when Mrs. Fleming introduced a big, handsome Algol, and as its dark companion a miniature black Dinah.

Additional features of Mina's personality were listed as 'very quiet, very earnest, very sincere, quick to sympathise, altogether magnetic ... none could have been more reticent of personal credit ... her own part in researches she unconsciously left inconspicuous ... she regarded her work as a high privilege. But she gave unstinted praise to her assistants.'

13.1. *Stars having Peculiar Spectra – Annals 56, Part 6*

Mina's main two instruments had been the 0.20-m Bache and Draper astrographs, each producing nearly 40,000 plates of size 20 × 25 cm covering 10°-square regions of sky. Additional photographs of spectra involved an objective prism and slight alteration to the telescope drive rate; Mina also reviewed all plates from the 0.60-m Bruce astrograph. Only small dispersions were achieved, between 2 mm and 7 mm typically for the smaller instruments. However these tiny barcodes were often all that Mina needed to trace the history of the heavens for a variety of objects, including:

1. New Stars. Ten of nineteen identified from their spectra, with novae differing from long-period variables by having a bright He hydrogen line, and occasionally a bright K calcium line.
2. Gaseous Nebulae. Spectrum P – typically showing continuous spectra with bright lines, including 59 discoveries by Mina.
3. Type V. Spectrum O – the most striking spectra with most light concentrated in two bright bands, one in the blue and the other in the yellow. After 13 visual discoveries of Wolf-Rayet stars between 1867 and 1884 the HDM plates took over, with 94 discoveries listed.¹⁹³
4. Stars having bright hydrogen lines. Type I stars with typically a bright H β line.
5. Spectroscopic Binaries, including Pickering's discovery of ζ Ursae Majoris (Mizar) and Maury's discovery of β Aurigae, both in 1889. Mina tabulated those brighter examples of Class A showing alternate single and double lines, including her own two discoveries of β Lupi in 1897 and ζ Centauri in 1899.
6. Variable Stars. Lists for Algol type, β Lyrae type, short and long-period variables tabulated; Mina credited herself with the discovery of four Algol-type variables between 1902 and 1910, one β Lyrae type in 1904 (RV Ophiuchi), and four short-period variables between 1901 and 1907 (including RR Lyrae in 1901).

13.2. *Her final catalogue*

Mina's final catalogue, not quite completed before she died, was published in Harvard *Annals* 71, Part II, in 1917 under the title *Spectra and Photographic Magnitudes of Stars in Standard Regions*. In 1884 Pickering had designated 48 regions of the sky for which a uniform system of standard magnitudes might be developed, using both photometric and photographic measures. In 1911 Mina completed her measures of 1434 stars between second and eleventh magnitudes, identifying between 12 and 60 stars per region for use in future investigations. This catalogue was subsequently extended to 19th magnitude by Annie Cannon.¹⁹⁴

13.3. *DASCH*

A year after Mina's death Pickering reflected: 'The greatest need is provision for a number of computers to utilize the vast amount of material contained in the Harvard collection of photographs. It may be compared to a library of 200,000 volumes with only a dozen readers.'¹⁹⁵

One hundred years later the Digital Access to a Sky Century @ Harvard (DASCH) project was underway using a custom-built high-speed scanner to digitize over 500,000 glass plates held by HCO.¹⁹⁶ At the time of writing (2017 February) 151,786 plates had been scanned and the plan for Time Domain Astronomy (TDA) was nearing a reality. Scanning *c.*400 plates per day would enable all the Plate Store to be digitized by 2018.

In 2016 January the Cambridge city water main below the Observatory ruptured, flooding a basement to a depth of one metre and requiring 62,000 plates to be rescued and frozen; an 18-month operation to thaw and photograph each plate prior to removing its paper sleeve and gently cleaning the photographic emulsion is planned.^{197,198}

Conclusion

More detailed biographies of female astronomers are needed. Williamina Fleming was an educated young woman when she first arrived in the United States in her brother's footsteps. Her marriage had proved unsuccessful and dreams of a fresh start might have been thwarted by a second pregnancy. Fortunately her new employer was willing to support some of her needs and keep open the opportunity of a permanent position. Mina proved herself an immensely valuable asset and quickly established herself as a leading astronomer in America.

Opportunities provided by advances in photography and spectroscopy coincided with the support, encouragement, and financial backing of Mrs Draper. The Henry Draper Memorial became the central pillar for the growth of Harvard College Observatory; its director skillfully assembling instruments, observers, and programmes for whole-sky surveys. The unprecedented amount of data arriving necessitated a corps of female

assistants, mostly appointed and motivated by Mina. The Harvard Plate Store quickly became the world's central repository for the photographic history of the heavens. In her detection of Eros Mina proved she could find the proverbial needle in the haystack.

Her discoveries – 1 supernova, 9 novae, 59 gaseous nebulae, the Horsehead Nebula, 2 spectroscopic binaries, 75 Wolf–Rayet stars, and 310 variable stars – secured her place in any astronomical hall of fame. But it was her unstinting loyalty, dedication, and outstanding effort that ensured HCO delivered its director's aspirations. Harvard Corporation never acceded to Pickering's requests for an assistant director; they did not need to, as Mina fulfilled this role admirably during the second half of her three decades at Cambridge.

By the time of the 1910 Solar Union meeting at Mount Wilson she ranked among the world's leading astronomers; in more enlightened times she would have received the Bruce Medal for her achievements. Today, with the exciting developments of the DASCH project, it is perhaps not too late to celebrate her life and pioneering achievements.

Acknowledgements

The need for this research was realized during the author's work on the Gill-100 project (see *The Antiquarian Astronomer*, 10, 2016 June, pp. 13–37) which investigated decisions taken during and prior to the 1887 Astrophotographic Congress in Paris. An additional query on the role of Harvard College Observatory from Ian Glass initiated action during the first half of 2016.

I am particularly grateful to Mark Hurn, Piet van der Kruit, Keith Lafortune, Robin Carlaw, Robin McElheny, and other reference staff at Harvard University Archives, all of whom have provided encouragement, access to archives, or responded to various queries. I also acknowledge the important help of works by Lyle Gifford Boyd, Tom Fine, Dorrit Hoffleit, Stefan Hughes, Bessie Zaban Jones, Pamela Etter Mack, Cecilia Payne-Gaposchkin, Howard Plotkin, Dava Sobel, and Grace Agnes Thompson. Dava Sobel's book *The Glass Universe* appeared in the final stages of preparation of this paper; the author wishes to thank her for sharing examples of her on-site research at Harvard University Archives.

The research presented here made extensive use of the Hathi Trust Digital Library; Harvard University Archives; Smithsonian/NASA Astrophysics Data System; and various sources retrieved online through Google Books and JSTOR Digital Library. I would also like to thank my wife Ann who has contributed significantly to the many discussions about Mina Fleming's life during the past year.

References and notes

1. Hughes, Stefan, *Catchers of the Light* (eBook, 2012), Vol. 8, pp. 686–703, hereafter Hughes (2012), includes a genealogy of the Stevens family. Hughes records only one son for Mina, but see Note 5.
2. Robert Stevens owned a large carving and gilding business which involved picture framing and work in gold-leaf. He pioneered the daguerreotype photographic process in Dundee; he died 1864 March 19. Mary Stevens joined most of her children in America in 1887.
3. Mina recounted her ankle injury in 1906 to 9-year-old Margaret Carnegie (1897–1990), daughter of Andrew and Louise Carnegie, the Scottish industrialist and philanthropist who were living in New York. Margaret had also suffered a serious ankle injury and was delighted to receive occasional educational gifts, jewellery, and small presents. See 'Miscellaneous Correspondence of W. Fleming' at Harvard University Archives. HUG 1396.
4. Thompson, Grace Agnes, 'Williamina Paton Fleming', *New England Magazine*, 48 (1912), 458–67, hereafter Thompson (1912). Mina instructed for five years in Broughty Ferry, a burgh adjoining Dundee.
5. Williamina Fleming married on 1877 May 26 at the United Presbyterian Church in Dundee. It is unknown if James Fleming accompanied his wife to Boston. It is usually suggested that he abandoned her when she became pregnant for the second time. By coincidence, at the time of their 1879 April wedding Robert and Anne Stevens were also expecting an October child. Writing to Louise Whitfield Carnegie (1857–1946) in 1905 Mina explained: 'Of my own two boys, only one lived to grow up.' Carnegie folder (Box 3), Pickering correspondence (UAV.630.17.5). The author is grateful to Dava Sobel for providing a transcription of this letter.
See also: Sobel, Dava, *The Glass Universe: How the ladies of the Harvard Observatory took the Measure of the Stars*, (Viking, 2016), p. 117, hereafter Sobel (2016). This modern appraisal of the work of the women at HCO is a welcome addition to the history of astronomy.
6. Mina's decision to include the full name of her employer on her son's birth certificate has been interpreted by some as implying Pickering was the father. The author has found no evidence to support this notion and considers it more likely that as the support of the Pickering family had proved immensely significant she had wished to honour his name.
7. The author has used a currency conversion of £1 = \$5 for this paper, with the assumption that costs have risen by a factor of 90 since the 1880s.
8. Useful biographies are: Bailey, Solon I., 'Biographical Memoir of Edward Charles Pickering 1846–1919', National Academy of Sciences (1932); Tenn, Joseph S., 'Edward C. Pickering: the Seventh Bruce Medalist', *Mercury*, Jan/Feb 1991, pp. 27–30; and Plotkin, Howard, 'Edward Charles Pickering', *Journal for the History of Astronomy*, 1990JHA..21..47P.
9. Tom Fine's website 'Harvard College Observatory History in Images' showcases his research of early archive illustrations for HCO. Another useful source is Schmidt, Richard E., 'The Tuttle of Harvard College Observatory: 1850–62', 2012AntAs..6..74S.
10. Letter from G. P. Bond to W. Mitchell written 1857 July 6, 1890PASP..2..300.

11. Mack, Pamela Etter, 'Women in Astronomy in the US: 1875–1920', BA thesis Harvard University (1977). Compared with domestic service or factory work, women considered astronomy jobs as highly desirable, due to good working conditions, companionship and reasonable duties. In 1875 room and board cost \$6/week so a \$500/year salary provided a 'minimum wage'. Teaching posts typically paid \$900/year but were scarce. Male assistants at Harvard, engaged in night observing or mechanical work, received \$800/year in 1887.
12. Friedrich Wilhelm Argelander (1799–1875) was the German astronomer responsible for the Bonner Durchmusterung, published 1852–9. At the Astronomische Gesellschaft meeting in Leipzig in 1865 a proposal to revise this star catalogue led to over a dozen observatories collaborating.
13. 1877 HCO *Annual Report*, 1877 November 26. After this date all Annual Reports were issued in the autumn of the year in question, usually in September.
14. 1877 HCO *Annual Report*. The last subscription had been in 1868 for the meridian circle. Pickering reasoned the scientific output of HCO could be doubled with an income of \$6000 (\$3500 for 5 assistants, \$1000 for salary increase, \$1000 for apparatus and books, \$1000 for publications). A \$2000 gift from Miss Harris helped. The cost of each volume of the HCO *Annals* was \$2000 (c.£36,000 today).
15. 1878 HCO *Annual Report*.
16. 1879 *Annual Report*. Refurbishment of the East Computing Room included repainting and papering prior to carpet-laying in 1880. It coincided with Mina's initial period at HCO, when she was assisting with book-keeping and accounting work part-time. Pickering was keen to develop his group of female assistants and sought Mina's advice on making their working conditions as pleasant as possible. She did not start on HCO payroll until 1881 and it is probable that Edward and Lizzie Pickering covered some of her expenses in the intervening period, especially her passage twice across the Atlantic.
17. Hoffleit, Dorrit, 'The evolution of the Henry Draper Memorial', *Vistas in Astronomy*, 34 (1991), 109–10, hereafter Hoffleit (1991).
18. Pickering's first RAS Gold Medal. Pickering's first survey was completed by 1881 August after which a 100-mm f/15 meridian photometer was constructed to extend the work to 9th magnitude.
19. Mina Fleming returned alone to Boston in 1881 April on a steamer from Glasgow. Edward Fleming remained in the care of his grandmother Mary Stevens (née Walker) for the next six years. It is possible that Pickering supported this arrangement financially as preferable to having a young child with his name in Cambridge. The situation became impossible to continue by 1887 September.
20. 'Venus Transit at HCO', *Proc Am Acad*, 18 (1883), 15–40.
21. The Drapers toured Europe in 1879, making visits to Huggins and Common and a presentation to the RAS on 1879 June 13.
22. Barker, George F., 'Memoir of Henry Draper. 1837–1882', National Academy of Sciences (1888).
23. Jones, Bessie Zaban, and Boyd, Lyle Gifford, *The Harvard College Observatory. The First Four Directorships, 1839–1919*, (Harvard University Press, 1971), hereafter Jones & Boyd (1971).
24. Pickering, Edward Charles, 'Researches upon the Photography of Planetary and Stellar Spectra. By the late Henry Draper. Results of Measurements by Professor E. C. Pickering', *Proc Am Acad of Arts and Sciences* xix 146, pp. 231–61; includes two plates showing the Drapers' observatory and telescopes at Hastings, New York.
25. Rumford Fund of American Academy grant.
26. Haley, Paul A., 'Entente céleste: David Gill, Ernest Mouchez, and the Cape and Paris Observatories 1878–92', *The Antiquarian Astronomer*, 10 (2016), p. 19, hereafter Haley (2016).
27. 1883 HCO *Annual Report* dated 1883 December 19. Pickering visited observatories at Greenwich, Oxford, Cambridge, Paris, Brussels, Bonn, Strasbourg, Berne, Geneva, Milan, Vienna, Berlin, and Potsdam, together with the private observatories of Huggins, Common, and Ranyard.
28. 'Astronomical Photography', *The Observatory*, 6 (1883), p. 149.
29. '1883 June 8 meeting of the Royal Astronomical Society', *The Observatory*, 6 (1883), 199–206.
30. During his European tour the Collegio Romano observatory in Rome was not visited; Angelo Secchi (1818–78) had died 5 years before Pickering's trip. Secchi had used a 160-mm flint objective prism of 12° refracting angle with the 240-mm Merz refractor in a visual study of the spectra of bright stars. Pickering planned to adopt a similar approach but using a short-focus astrograph to secure wider fields and sensitive dry plates to record the spectra of fainter stars. This innovative plan was kept secret as he first needed to secure funding.
31. Pickering, E. C., 'Stellar Photography', *Memoirs of the American Academy of Arts and Sciences*, 11 Pt IV (1886).
32. Letter from Pickering to Mrs Draper, 1885 May 17, quoted in Jones & Boyd (1971), p. 227.
33. Boyd, Lyle G., 'Mrs Henry Draper and the Harvard College Observatory: 1883–1887', *Harvard Library Bulletin*, 17 (1969), p. 75, hereafter Boyd (1969); includes a review of key correspondence with Pickering.
34. Haley (2016) p. 15 and pp. 21–22. Jean Chacornac (1823–73) visually mapped stars to 13th magnitude along half the ecliptic; Paul Pierre Henry (1848–1905) and Prosper-Mathieu Henry (1849–1903) were continuing this project in Paris. Each ecliptic chart covered 5° square and typically contained 1500 stars. Visual mapping became impractical when the Milky Way regions were attempted. The Henry brothers constructed a 0.16-m f/13 astrograph in autumn 1884 and then a 0.33-m f/10 instrument to match the Chacornac charts; this latter instrument was adopted by the French Government for the Carte du Ciel project in 1886 April. Christian Henry Frederick Peters (1813?–90) worked to a similar scale with each chart averaging 3000 stars to 14th magnitude. It is probable that Pickering discussed the astrograph approach with the Henry brothers, or more probably the director of Paris Observatory Ernest Mouchez (1821–92), during his summer visit of 1883.
35. Pickering, E. C., *An investigation in Stellar Photography*, Am. Acad. Memoir (1886), presented 1886 March 10.
36. Between 1885 and 1923 the 0.20-m Bache astrograph took 53,754 plates, averaging >1400 plates per year; Pickering's plan was ambitious and achieved an amazing output. 1891AnHar..26..1P, Table 1, gives a complete catalogue of dates and exposures. The first Bache

- plate, taken on 1885 August 4, was a 48-minute exposure of the north celestial pole.
37. Mrs Draper supported HCO financially for 28 years, contributing \$387,000 (c.£7 million today) together with major instruments.
 38. Gerrish graduated from MIT in 1887 but had begun working in 1885 at the nearby Blue Hill Meteorological Observatory under director Abbot Lawrence Rotch (1861–1912). His mechanical skills proved useful at HCO where he devised several engineering solutions to improve the efficiency of the instruments; the Gerrish polar telescope is one such example.
 39. Hearnshaw, John B., *Astronomical Spectrographs and their History*, (Cambridge, 2009), pp. 143–5. The four large prisms were made by splitting thick glass plates diagonally. They were fitted as drawers within a square brass box which weighed over 45 kg and was fixed in front of the 0.28-m objective; changing the number of prisms must have required a significant rebalancing of the telescope.
 40. Barker, George F., ‘On the Henry Draper Memorial Photographs of Stellar Spectra’, Am Phil Soc presentation, 1887 April 1.
 41. Pickering, Edward C., *Henry Draper Memorial. First Annual Report* (John Wilson, 1887), p. 8.
 42. Letter from Pickering to Mrs Draper 1886 October 13; Boyd (1969), 93–4.
 43. This letter suggests that Gerrish and Farrar were effectively on ‘equal pay’ at this time (c.£10,800 today). Gerrish would have received a pay rise after his graduation from MIT in 1887.
 44. Mack, Pamela Etter, *Women in Astronomy in the United States 1875–1920* (Harvard University, 1977), p. 65. Letter from Pickering to Mrs Draper 1886 December 31, quoted in Boyd (1969) p. 95. Nettie Farrar married Charles Harris of California and they moved to Texas.
 45. Today these are known as WR 139 and WR 133. Charles Wolf and George Rayet discovered three in Cygnus in 1867; Respighi found one in 1871; Pickering three in 1880/1; and Ralph Copeland six in 1883–4, all by visual means.
 46. Pickering, Edward C., ‘Draper Memorial photographs of stellar spectra exhibiting bright lines’, *Nature*, 34 (1886), p. 440.
 47. The engineer Uriah Atherton Boyden (1804–79) had died eight years earlier. Pickering first contacted the trustees of his estate in 1882. HCO gained control of the fund in 1887 February; this facilitated an immediate grant of \$20,000 and an annual income of \$11,000 (c.£360,000 and c.£200,000/year respectively today).
 48. The attorney Robert Treat Paine (1731–1814) was an amateur astronomer and loyal supporter of Harvard College.
 49. Fleming, Williamina, ‘Harvard College Observatory Astronomical Expedition to Peru’, *PASP*, 4 (1892), 58–62.
 50. Haley (2016) p. 26 section 9.4, ‘Pickering’s alternative plan’, summarizes the Harvard approach; see footnote 90 on p. 36 for the 1903 Harvard ‘map of the sky’.
 51. Winterhalter, Albert G., ‘The International Astrophotographic Congress and a visit to certain European observatories and other institutions’, Washington Observations for 1885 (Washington US Naval Observatory, 1891) 55–8, hereafter Winterhalter (1891). This useful summary provides an independent version of events at the Paris Congress in chronological order. This occupies the first 74 pages of the 350-page report which continues with a series of observatory visits, including UK.
 52. Letter from Gill to Pickering, 1891 April 8. Jones & Boyd (1971), p. 210.
 53. Hughes (2012) p. 689 describes how on 1887 September 10 young Edward Fleming boarded the Montreal Ocean Steamship *SS Prussian* at Glasgow docks bound for Boston. He was accompanied by his grandmother Mary Stevens (50) and cousins Andrew (11) and Joanna Stevens (11); none ever returned to Scotland.
 54. Edward and Lizzie Pickering enjoyed a successful marriage of 34 years but had no children. It is possible that they supported Mina and her son’s education in some way. This hypothesis explains how, despite her modest salary, Mina was able to send her son to MIT and pay for extra private tuition at the same time as supporting her mother and running a home. Jones & Boyd (1971) p. 394 hints at this possibility when describing Mina’s ‘strong personal attachment’ to Pickering. By 1906 Mina’s accommodation was also supporting her younger brother Charles James Stevens (1863–1920) and his two sons, Charles (12) and Malcolm (10), their mother having died in 1904 November. At this time she also had two dogs, a Boston terrier and a beagle hound. Pickering’s 1919 Will & Codicil included no provision for Edward Fleming; the author is grateful to Robin Carlaw (Harvard University Archives) for supplying a copy of these documents.
 55. Reed, Helen Leah, ‘Women’s Work at the Harvard Observatory’, *New England Magazine*, 12 ii (April 1892), p. 167.
 56. Jones & Boyd (1971) pp. 189–93. The Observatory Pinafore was written in 1879 August but not performed until 1929. One reason was the early death of Joseph McCormack in 1880, from typhoid, which left HCO staff disinclined to stage a musical parody of H.M.S. Pinafore. It can be accessed online at: <http://hea-www.harvard.edu/~jcm/html/play.html>. It includes the notion of Mina teaching HCO staff a Highland polka, had she not returned to her native land.
 57. McCarthy, Martin F., ‘Fr. Secchi and Stellar Spectra’, *Popular Astronomy*, 58 iv (1950), 153–68.
 58. Pickering E. C., ‘A Fifth Type of Stellar Spectra’, *Astronomische Nachrichten* 127 i (1891). Fleming prepared most of this paper. Fleming, Williamina, ‘A Sixth Type of Stellar Spectra’, *Harvard Circular* 145, 1908 December 1.
 59. Hoffleit (1991) pp. 120–3. See also: Hoffleit, Dorrit, ‘Pioneering Women in the Spectral classification of Stars’, *Phys. Perspect.*, 4 (2002), 370–98 which includes a section on Mina pp. 371–81. At this time (1886–91) the idea of stellar temperature being linked to spectra had not been proposed.
 60. Misses R. W. Gifford, Annie Masters, Jennie Rugg, and Nellie Storin also worked at HCO at this time, but due to marriage mostly for only two years. The job of assistant required ‘knowledge of ordinary arithmetic and legible handwriting’; it was mainly clerical, tedious and repetitive but nevertheless viewed as respectable work for an American woman at the end of the 19th century.
 61. The arrival of three graduate women at HCO might have undermined the role of Mina Fleming. In practice only Maury’s arrival seems to have caused a problem. This may well have arisen from her lowly pay of

- 25c per hour but probably resulted from her preference to speculate about the evolution of stars, which Pickering found difficult to restrain.
62. Maury calculated the orbits and periods of revolution for the first two spectroscopic binaries; this involved analysis of plates taken across 70 nights at HCO in 1889.
 63. Cecilia Payne-Gaposchkin, recalling Maury as an older woman when she periodically returned to HCO, described her as 'sensitive, imaginative, affectionate ... a rejected sort of person'. She was very talkative and undoubtedly found the routine atmosphere of HCO taxing.
 64. *The Spectra of Bright Stars* involved analysis of 4800 photographs of 681 bright northern stars; Annie Cannon's work (Part II of Vol. 28) appeared three years later, for 1122 bright southern stars. Mina edited both volumes.
 65. Barnard 33/IC 434. The compiler of the first *Index Catalogue*, J. L. E. Dreyer (1852–1926), omitted Fleming's name; research by Stephen Waldec and Martha Hazen, 1990PASP..102.1337W.
 66. 1890AnHar..18..113P, Vol. XVIII. No. VI, 113–17.
 67. 1890AnHar..119P, Vol. XVIII. No. VII, 119–214.
 68. Haley (2016), p. 14.
 69. Mina's work built on Nettie Farrar's initial survey of 117 polar stars, illustrating how Pickering planned many projects in cycles expecting to add further results as the technology improved and his assistants developed their skills. Leavitt and Fleming would both later extend this work.
 70. Spectra of the Draper astrograph were one-third the length of the Bache ones; importantly, red stars could now be investigated. The Wolsingham Observatory Circulars, by Rev. T. H. E. C. Espin (1858–1934), for 1887–1900 were received at HCO; his visual study of variable stars, red stars, and remarkable spectra were often included by Mina in her references.
 71. 1890AnHar..27..1P 'The Draper Catalogue of Stellar Spectra'. Mina's 1890 papers included: 1890AN..123_383P, 'Spectra of δ and μ Centauri' dated January 16; 1890AN..124_175P, 'New Variable in Caelum' dated February 26; 1890AN..124_271P, 'New Variable Star in Cygnus' dated April 16; 1890AN..125_155P, 'Stars having Peculiar Spectra' dated July 1; 1890AN..125_361P, 'New Variable Star in Scorpius' dated July 31; 1890AN..125_363, 'Stars having Peculiar Spectra' dated September 8; 1890AN..125_365, 'New Variable Star in Sagittarius' dated September 12; and 1890AN..126_117P, 'Stars having Peculiar Spectra including new Variables in Triangulum and Hydra' dated October 21. 1891AnHar..26..1P 'Preparation and Discussion of the Draper Catalogue Part I'. Despite carrying out the bulk of the classification and supervising the entire production of the catalogue Mina was not listed as co-author of either volume. Instead Pickering credits her work on page xxiv of the Introduction.
 72. 1893 March 2 transfer at rate of 6000 plates per hour. Each box contained one hundred 20 × 30-cm plates. The building measured 18 × 9 m with three storeys including a basement. A room for examination and discussion was included.
 73. 1892 HCO *Annual Report*. \$9200 donations, about two-thirds the cost raised; 1896 HCO *Annual Report* confirms cost of \$15,000; 1904 HCO *Annual Report* \$20,000 anonymous gift used partly for 9-m square three-storey extension.
 74. 1893PASP..55..220 ... 'The Bruce Photographic Telescope' pp. 221–2 includes a description of the second-floor storage room for the plates: 'Two large cabinets run through the centre of the room, and are divided into compartments, each capable of holding 100 plates. There are 120 of these compartments, so that each cabinet will hold 12,000 plates. One is devoted to the photographs taken at Cambridge and the other to those taken in Peru. The plates taken by the new [Bruce] instrument will be larger, so that a cabinet with larger compartments has also been prepared, which will hold the result of about a year's work.'
 75. 1890AN..125..361P 'New Variable Star in Scorpius', 1890 July 31.
 76. 1892AN..131..61 'A New Variable Star in Aries', 1892 September 9.
 77. 1892AN..129..112 'Ueber den neuen Stern in Auriga', 1892 February 15.
 78. 1891AN..128..377P 'Distribution of Energy in Stellar Spectra', 1891 October 31.
 79. 1891 HCO *Annual Report* pp. 175–6. Including this discovery might have prompted Maury to return to HCO as she regarded β Lyrae as 'her work'.
 80. *The Sidereal Messenger* (10 volumes) preceded *Astronomy and Astrophysics* (3 volumes) which in turn was succeeded by *The Astrophysical Journal* from 1895. Hale and James Edward Keeler (1857–1900) collaborated with Pickering. When *AJ* launched Hale overcame a funding deficit by contacting Pickering. A \$1000 cheque (c.£18,000 today) duly arrived from Miss Bruce; this enabled better-quality illustrations to be used. HCO supported Hale's endeavours by supplying regular papers and discovery announcements. *The Sidereal Messenger* and *AstAp* can be searched using the Hathi Trust Digital Library.
 81. 1892AstAp..11..418 'Stars having Peculiar Spectra', 1892 April 14; see also 1892AstAp..11..765, October 10; and 1892AstAp..11..945, 1892 November 10.
 82. The World's Columbian Exposition celebrated the 400th anniversary of Columbus. Hale was the main organizer and was supported by astronomer George Washington Hough (1836–1909). Hale promoted the emerging science of astrophysics by including presentations on spectrum analysis, astronomical photography, and stellar photometry.
 83. It is likely that Mina also prepared some of Pickering's paper 'The Constitution of the Stars' which appeared just before the Congress in 1893AstAp..12..718. Hale had invited Pickering to present his paper but testing of the new Bruce telescope was underway at Cambridge and the Director sent his brother William instead; Mrs Draper also attended the Exposition and would have seen the enlarged photographs taken during her visit to HCO two years earlier – see Fig 12. See also Sobel (2016), pp. 54–5.
 84. 1893AstAp..12..683 'A Field for Woman's Work in Astronomy', 1893 August 4. Brück, M. T., 'Lady Computers at Greenwich in the early 1890s', *QJRAS*, 36 (1995), 83–95, provides a UK perspective for the short-lived (1890–5) experiment of employing female assistants at this time. See also: Reed, Helen Leah, 'Women's work at the Harvard Observatory', *New England Magazine*, 6 (1992), 165–76. This paper includes an image of Mina in her earlier years at HCO.
 85. Ogilvie, Marilyn Bailey, *Women in Science: Antiquity through the 19th Century*, (MIT, 1986), p. 153.

- See also Haley (2016), pp. 29–32.
Dorothea Klumpke (Klumpke-Roberts after 1901) had begun working for Ernest Mouchez in 1887 and supported him significantly during the last five years of his life, especially after his deafness became acute.
86. 1893AN..134..59P ‘Entdeckung eines neuen Sterns im Sterbilde Norma’, 1893 October 29, gives details of Pickering’s telegram to Kiel. 1893AN..134..101P ‘A New Star in Norma’, 1893 November 9, gives more details of Mina’s discovery of her first nova – the first nova detected by spectral photography.
 87. 1893AN..134..181 ‘The New Star in Norma’, 1893 November 28. Pickering describes the two methods Mina used for measuring the position of images.
 88. The Bruce plates measured 35 × 43 cm.
 89. *Cambridge Chronicle*, Vol. L, no. 17, p. 2, ‘Something about women astronomers employed at Harvard Observatory’, (1895 April 27). At this time Mina was living in Frost Street, Cambridge, but planning a new residence to be built in Huron Avenue, near Brendon Street, a ‘stone’s throw’ from HCO.
 90. HarCi001, 1895 October 30. Mina’s second nova.
 91. HarCi004, 1895 December 20.
 92. Caldwell, N., and Phillips, M. M., ‘Star formation in NGC 5253’, 1989ApJ..338..789C, includes the Harvard discovery plate taken in 1895 July. The first extragalactic supernova discovery was by Hartwig 10 years earlier: SN 1885A (S Andromeda); the second was by Wolf, 1895A (VW Vir) in NGC 4424.
 93. HarCi006, 1896 March 10. Mina was checking between 24 and 66 plates for each variable star.
 94. HarCi007, 1896 June 5. HCO were also now confirming variable star discoveries made by astronomers across the world.
 95. HarCi009, 1896 July 9.
 96. 1894AN..137..71, 1894 November 21.
 97. HarCi011, 1896 August 31.
 98. 1897AnHar..28..1M, *Spectra of Bright Stars*. Maury studied 4800 plates for this HDM investigation which began in 1888. The report is 128 pages long, including supplementary notes relating to the discoveries of the spectrum of helium.
 99. While Maury was examining spectra up to 80 mm long Fleming continued to work with the 0.20-m Bache and Draper astrographs with spectra between 2 and 6 mm length, produced by objective prisms of refracting angle 5° and 13° respectively.
 100. <http://ocp.hul.harvard.edu/ww/fleming.html> links to Mina’s 1900 Journal. At this time she was editing Miss Cannon’s work and noted: ‘This takes more time and concentration of thought than any manuscript I have worked on since we put Miss Maury’s volume (XXVIII Pt. I) through the printer’s hands’.
 101. Annie Cannon began on payroll in 1897 September. Lafortune, Keith, ‘Women at the Harvard College Observatory, 1877–1919: Women’s Work, The New Sociality of Astronomy and Scientific Labour’ unpublished MA thesis, University of Notre Dame, 2001; hereafter Lafortune (2001).
I am grateful to Keith Lafortune for a copy of his thesis. It examines three points of view: 1. women’s work in the sciences; 2. more collaborative industrial approach; 3. a cultural study of women in the workplace at HCO. For Annie Cannon he includes a letter from Pickering, dated 1896 January 15: ‘Spend as much time at the Observatory as you wish ... I have spoken to Miss Leavitt ... one or more telescopes will also be available for the observation of variable stars which you wish to make.’
 102. HarCi016, ‘The Spectrum of ζ Puppis’, 1897 January 12.
 103. In 1898 June Pickering recommended Annie Cannon for a Radcliffe degree. She had worked five hours a day on HCO research for a year, observing 1–3 hours with the west equatorial on 63 evenings (365 observations of variables) and continued the work of Miss Maury, examining 1400 photos of ~400 stars to classify their spectra.
 104. 1895 HCO *Annual Report* (the 50th). Pickering’s three-month trip to Europe was probably a vacation; he did not attend RAS meetings in April, May, or June, possibly due to the criticism received from RAS President Andrew Ainslie Common (1841–1903).
 105. 1903 HCO *Annual Report*. On 1903 May 23 Pickering completed his one millionth photometric setting (39,796 with 50-mm, 643,308 with 100-mm, and 316,896 with 300-mm meridian photometers). He regularly shipped the 100-mm instrument to Peru for Solon Bailey to complete surveys below –30° declination. Usually Pickering worked from 7 pm to 11 pm. Visual photometry to an accuracy of 0.1 magnitude was superseded by advances in photographic emulsions after 1912.
 106. 1895ApJ..1..27P, 1894 December 14. Pickering used this paper for his talk but updated the number of variables discovered by Mrs Fleming to 80; she had also confirmed a similar number suspected by other observers. Vogel classification subscripts were now in regular use for spectra.
 107. 1895ApJ..1..411F, 1895 April 9, ‘Eleven new variable stars’; 1895ApJ..2..198F, 1895 July 5, ‘Seven new variable stars’; 1895ApJ..2..354F, 1895 November 19, ‘Eight new variable stars in Cetus, Vela, Centaurus, Lupus, Scorpio, Aquila and Pegasus’; HarCi006, 1896 March 10, ‘[14] new variable stars’; HarCi007, 1896 June 5, ‘Ten new variable stars’; HarCi010 ‘Six new variable stars’, 1896 August 13.
 108. 1897AnHar..26..193, *Miscellaneous Investigations of the Henry Draper Memorial*. Mina’s investigation, ‘The Spectra of Stars in Clusters’, is Chapter XIV, pp. 260–86.
 109. Hoffleit (1991), p. 125. Mina investigated 975 star spectra in seven open clusters: Pleiades, Praesepe, Carina, NGC 3523, Coma, NGC 6405, and NGC 6475.
 110. Eleven female assistants attended including Imogen Eddy, Mina Fleming, Edith Gill, Lillian Hodgdon, Eve Leland, Antonia Maury, Mabel Stevens, Anna Winlock, Louisa Winlock, Gertrude Wolfe, and Ida Woods.
 111. Fleming, M., ‘Stars of the fifth type in the Magellanic Clouds’, in Proceedings of the Second Conference of Astronomers and Astrophysicists, *AptJ* 8 (1898), p. 232.
 112. 1898ApJ...8_193. The youngest delegate was 18-year-old MIT student Edward Fleming, Mina’s son, who would become a naturalized American in 1904 January, three years before his mother.
Donaghe, Harriet Richardson, 1898PA..6..481D, ‘Photographic Flashes from Harvard Observatory’, p. 483 is the source for Pickering’s quote.
 113. HarCi019, 1897 September 28. Some of these stars were also claimed by Stewart at Arequipa. Two later Bruce plates revealed 15 more in the LMC and one in the SMC.

114. 1898AN...147..141R, Entdeckung eines neuen Planeten 1898 DQ. French astronomer Auguste Honoré Charlois (1864–1910) at Nice Observatory photographed Eros on the same evening but did not announce the discovery until after Witt.
115. HarCi034, Witt's Planet DQ, 1898 September 30. Both Wendell and Fleming were working on Eros by September 6; the photographic brightness was less than the photometric brightness, so nearly 13th magnitude.
116. Falese, J., and Sliski, D., 'Asteroid 433 Eros, Part 1', <http://albibio/gazette/asteroid-433-eros-part-1/> 2013 October 17. Illustrates four labelled images of Eros on HCO plates.
117. HarCi036, Witt's Planet (433) DQ, 1898 December 26.
118. HarCi037, Additional observations of Eros (433), 1899 January 16, describes Mina's continuing work, although she is not mentioned in the text. Instead Pickering used the opportunity to explain how the small 2° fields of the astrographs at Greenwich and Oxford were undermining their attempts to photograph Eros; Pickering was skilled at finding ways to praise the search capabilities of his doublet-lens astrographs.
119. HarCi051, Positions of Eros (433) in 1893, 1894 and 1896, 1900 June 7. It must have been a relief for Mina to delegate further study on Eros to her assistants; Eve Leland, Anna Winlock, and Ida Woods completed further measurements and reductions.
120. HarCi020, 'Spectrum of a Meteor', 1897 November 8.
121. HarCi031, 'The November Meteors', 1898 May 30.
122. HarCi035, 'The November Meteors in 1898, 1898 November 19'.
123. HarCi040, 'Photographing Meteors', 1899 February 20.
124. HarCi021, 'A New Spectroscopic Binary', 1898 January 1.
125. HarCi024, 'New Variable Stars', 1898 January 31.
126. HarCi029, 'Variable Stars of Short Period', 1898 May 21.
127. HarCi032, 'Stars having Peculiar Spectra', 1898 June 21. Annie Cannon's investigation of Stars resembling ζ Puppis is in the same *Circular*.
128. ApJ1898..8..233F, 'Classification of the Spectra of Variable Stars of Long Period'.
129. HarCi042, 'A New Star in Sagittarius', 1899 March 14. Mina's fifth nova discovery – a nice way to celebrate her new role as Curator of Astronomical Photographs.
130. 1900ApJ..12..52P, 'A New Star in Aquila', 1900 July. See also HarCi056 'Anderson's New Star in Perseus', 1901 February 27; the final paragraph gives spectrum details observed by Mina.
131. This was Pickering's fourth trip to Europe. He first crossed the Atlantic in 1870 for the total solar eclipse in Spain, then in 1883 for a vacation and tour of observatories, and another three-month vacation in 1895. On this fourth trip he left his wife to represent him at Paris while he returned to HCO. One possible reason was the Georgia solar eclipse on May 28 to which a number of staff travelled south to observe. The Exposition Universelle of 1900 was a world's fair in Paris from April to November and was visited by c.50 million people; it included the 1.25-m refractor, which was never completed.
132. 1900MNRAS..61..293.
133. <http://oasis.lib.harvard.edu/oasis/deliver/~hua09003> The Chest of 1900 includes eight document boxes and eleven envelopes of photographs to mark the end of the 19th and beginning of the 20th century. The wooden chest was sealed until 1960 and re-examined in 1999; it covers the month of 1900 March/April. Lafortune (2001) includes a quote from an undated draft letter from Mina to Louise Carnegie: 'Please do not place too high a value on my work. I have only done the best I could with what was given to me and I do often feel that someone else with my opportunities might have done better' but the draft statement is crossed out. Papers of Williamina Fleming Misc. Correspondence HUG 1396.
134. Lafortune (2001), Appendix 2.
135. 1900ApJ..12..84P, 'Harvard Observatory Expedition'. No glass plates were secured due to the instrument being knocked at the critical moment.
136. MIT *Technology Review*, vol. II, no. 3 (1900), 'The Georgia Solar Eclipse'. See also Sobel (2016), p. 98. Another member of the HCO group was Annie Cannon. For Mrs Draper this was her second solar eclipse – she had spent the 1878 eclipse inside a tent, calling out time signals to her husband's group outside.
137. 1901AnHar..28..129C. Cannon chose not to use Maury's scheme of 22 classes for bright northern spectra.
138. Concord Avenue marks the southern boundary of HCO. Cannon's diaries for 1894, 1905, 1907–11, and later years can be accessed via Harvard University Library. HUGFP 125.2 Box 1.
139. HarCi054, 'Sixty-four New Variable Stars', 1901 January 24.
140. RR Lyrae was discovered by Fleming in 1900; earlier examples of this class included U Lep and S Ara, together with cluster variables found by Solon Bailey.
141. HarCi060, 'Objects Having Peculiar Spectra', 1901 July 6.
142. HarCi065, 'A New Algol Variable +43° 4101', 1902 May 6. The star was at maximum brightness of mag. 8.9 on 388 plates; 19 plates showed it at mag. 9.3 or fainter. Pickering was delighted that the HCO Plate Store, which now covered 14 years, could reveal such discoveries.
143. 1903AnHar..48..91P, 'A Provisional Catalogue of Variable Stars'. In 1880 about 200 variable stars were known.
144. HarCi070, 'Nova Geminorum Before its Discovery', 1903 April 3.
145. 1903 HCO *Annual Report*, p. 253. In a letter to Mrs Draper, Pickering described the 'suitable arrangements' for Mina to work on the Southern Draper Catalogue at home in the evenings: 'a measuring apparatus has been made for her and a recorder provided'. Sobel (2016), p. 108.
146. HarCi084, 'Carnegie Grant of 1903', 1904 August 24. The HCO Plate Store was growing at ~10,000 plates per year.
147. Ida May Stevens was the 34th female assistant at HCO. She was born in Cambridge in 1882, the second child and only daughter of Robert Stevens and Anne Emerson. At this time she was the youngest female employee. In 1907 she married and became Mrs Garret; she left HCO in 1909 after five years. Her Aunt Johanna completed 17 years at HCO; she was

- awarded a gold medal by the AAVSO for discovering the first nova in Lyra.
148. HarCi076, 'Stars Having Peculiar Spectra', 1904 March 21.
 149. HarCi099, 'A Probable New Star, RS Ophiuchi', 1905 May 15. Annie Cannon deduced the light curve.
 150. RS Ophiuchi is now classified as a recurrent nova, and consists of a red giant and a white dwarf in close orbit. Eruptions occur about every 20 years, typically reaching 5th magnitude; at other times the star remains at 12th magnitude.
 151. HarCi106, 'H1175 Nova Aquilae, No. 2. 185604', 1905 September 23.
 152. They would have visited the laboratory dedicated to the memories of the pioneering work of Henry Draper and John Draper.
 153. The four other women astronomers were: Caroline Herschel (1750–1848), Margaret Lindsay Murray Huggins (1848–1915), Mary Somerville (1780–1872), and Agnes Mary Clerke (1842–1907); Anne Sheepshanks (1789–1876) was also honoured for her gifts to astronomy.
 154. *Wellesley College News*, Vol. 5, No. 34, p. 1, 1906 July 11. Mina was appointed Honorary Fellow in the Department of Astronomy at Wellesley College.
 155. HarCi111, 'Stars Having Peculiar Spectra. 13 new Variable Stars', 1906 February 16; HarCi117 183390, 'A new Algol Variable. –30° 16169. H 1236', 1906 May 20.
 156. 1906HarCi111, 'Spectra of Known Variables', 1906 February 16, p. 3. Also see Astronomy Picture of the Day (APOD) 2015 September 17.
 157. Mrs Lizzie Wadsworth Pickering (1849–1906) was the daughter of Jared Sparks, the President of Harvard College 1849–53. She supervised the grounds of HCO and was an expert on floriculture, with floral displays rivalling the botanic gardens. She introduced university teas for college students and was patroness of Harvard plays and a Cambridge society leading hostess. She was buried in Mount Auburn Cemetery, Cambridge. See also Sobel (2016), p. 119.
 158. HarCi123, 'Photographs of Faint Stars', 1907 January 19. HCO specialized in information for any star to 13th magnitude covering a period of 20 years.
 159. Mina recounted her fire-fighting experience to young Margaret Carnegie, explaining their monthly drills and system of telephone rings used to pinpoint the location of any fire on the HCO site. HUG 1396.
 160. HarCi124, 'Stars Having Peculiar Spectra. 18 new Variable Stars', 1907 January 26; HarCi131 'Group of Red Stars near Nova Velorum', 1907 October 3; HarCi132 'Stars having Peculiar Spectra. 15 New Variable Stars', 1907 October 15.
 161. Henrietta Leavitt continued the NCP work until 1921, identifying 46 stars from 4th to 21st magnitude using almost 300 plates taken with apertures from 13 mm to 1.5 m.
 162. Margaret Harwood became director of the Maria Mitchell Observatory in 1916 and supported the development of Harvard Astronomical Fellowships for Women with the help of Pickering.
 163. 1907AnHar..47..1F, 'A Photographic Study of Variable Stars'; 113 pages of Mina's research.
 164. Eve Leland, Louisa Wells, Sarah Breslin, Mabel Gill, and Mabel Stevens assisted Mina with the identification and computation of the comparison stars.
 165. Mina's American citizenship is dated 1907 September 7. Sobel (2016), p. 127.
 166. Tenn, Joseph S., 'A Brief History of the Bruce Medal of the A.S.P.', *Mercury*, 15 iv (1986), 103–11.
 167. Letter from Pickering to Gill, 1907 March 27, Royal Geographical Society with The Institute of British Geographers, The Gill Collection (DOG/125). This source consists of four boxes with 34 files and 1000 letters consisting mainly of correspondence from astronomers to David Gill. They are designated DOG/1–DOG/192 and have been transcribed by the author.
 168. 1908AnHar..50..1P, 'Revised Harvard Photometry – observed with the 2-inch and 4-inch Meridian Photometers'. Mina acknowledged the assistance of Florence Cushman, Mabel Gill, Amy McKay, and Mabel Stevens from her team.
 169. HarCi145, 'A Sixth Type of Stellar Spectra', 1908 December 1. See also Hoffleit (1991), p. 139, for a discussion of Class R stars.
 170. 1908ApJ..28..250, 'Astronomical and Astrophysical Society' includes Mina as the only female presenter. An account of the meeting is in JRASC..2..255–60 (1908) but does not include Mina at the event.
 171. 1909PA..17..463–4 and 1909PA..17..588. Mina's paper was 'A Photographic Spectrum of a Meteor'.
 172. *The Salt Lake Tribune*, Utah, 1909 August 22, p. 20, mentions this was Mina's first trip to the far west. Her son Edward was then a chemist in charge of a laboratory at Garfield.
 173. Hertzsprung's *Zur Strahlung der Sterne* was published in 1905 on stellar magnitudes and luminosities. Maury's work was duly acknowledged in 1922 by the IAU when they modified Cannon's scheme to include the prefix 'c' for stars with narrow sharp lines.
 174. Holberg, Jay B., *Sirius: Brightest Diamond in the Night Sky*, (Springer, 2007), 114–17. Russell published his recollection of Mina's involvement in 1944.
 175. 40 Eridani is a triple-star system 16.5 light years away, first observed by William Herschel in 1783. The primary is magnitude 4.4 and of spectral class K1 (an orange dwarf). The 9th-magnitude companion B is the most easily observed white dwarf for amateur astronomers. An 11th-magnitude component C is a red dwarf in orbit around the white dwarf. For *Star Trek* fans there is an interesting link between Mina Fleming and Mr Spock: the planet Vulcan was reputedly located within the 40 Eridani system!
 176. The Solar Union had been started by Hale in St Louis in 1904 September, meeting again in Oxford in 1905 September and Meudon in 1907 May. It was a forerunner of the International Astronomical Union.
 177. Plotkin, Howard, Edward Charles Pickering's Diary of a Trip to Pasadena to Attend Meeting of Solar Union, August 1910. This fascinating account by Pickering provides a real insight into both the journey and organization of this major conference. Curiously Mina (the only other HCO delegate) is not mentioned once.
 178. 1910JRASC..4..356C, 'The Mount Wilson Conference of the Solar Union' by C. A. Chant, pp. 356–72, and 1910PASP..22..169W, 'The Fourth Conference of the International Union for Co-operation in Solar Research' by H. C. Wilson, pp. 169–79, provide complementary summaries of this event.

179. Mary Walker (1832–1910) died September 6; at this time Mina and Edward were in Salt Lake City.
180. *Harvard Bulletin* 426, 1910 October 1.
181. *Harvard Bulletin* 427, 1910 October 13.
182. 1911ApJ..33..260, ‘Correspondence concerning the classification of stellar spectra’, pp. 260–300. A fascinating account of the views of astronomers across the world; the adoption of ‘absolute magnitude’ and its link to the luminosity of stars had been introduced by Kapteyn in 1902, but would not be ratified until 1922. See also: Hughes, David W., 2006JAHH..9..173H, ‘The Introduction of Absolute Magnitude (1902–22)’.
183. 1915JRASC..9..203C, ‘The Henry Draper Memorial’ by Annie J. Cannon gives a useful summary. Cannon succeeded Fleming as Curator but remained on HCO payroll until 1938. During 1911–15 she completed classifications of stars to 8th magnitude for the new HD catalogue. These were published 1918–24 and covered 225,300 stars. Cannon then extended her work to fainter magnitudes up to 1936 (she was then aged 73); she died 1941 April 13.
184. 1912AnHar..56...165F, ‘Stars having Peculiar Spectra’, pp. 165–226 with two plates.
185. Mina was living at 52 Concord Avenue, Cambridge, in 1911. Her autopsy showed blood poisoning in kidneys and spleen, so recovery from pneumonia was unlikely.
186. 1911 HCO *Annual Report*.
187. Thompson (1912). See also Pickering, E., *Harvard Graduates’ Magazine*, vol. 20 (1911), 49–51. Pickering’s eulogy for Mina can be accessed through the Hathi Digital Trust Library.
188. 1912MNRAS..72...261.
189. 1911ApJ..34..1, ‘Williamina Paton Fleming’.
190. *Cambridge Tribune*, 1911 May 27. Interment was at Mount Auburn Cemetery, Cambridge. Founded in 1831 it was the first large-scale landscaped burial ground set in tranquil surroundings. The final resting place of Edward Pickering and his wife is located nearby. Lafortune (2001), p. 145, states that Pickering is in lot #3401 and Fleming, a short distance away towards Harvard Square, in lot #6188. *Cambridge Chronicle*, 1911 May 27. Mina died on Sunday afternoon at New England Hospital. Her funeral was held Tuesday afternoon at her home, 52 Concord Avenue, with Rev. Joel Hastings Metcalf (1866–1925); the Harvard quartet played three hymns. Her son was working in Chile at the time; he died in 1951. Metcalf was a skilled optician who made a 0.40-m f/5.25 doublet and a 0.25-m f/4.9 triplet photographic lens for HCO. The former instrument was installed in 1910 and used curved 20 × 30-cm plates. The Metcalf triplet anastigmat was used at both Arequipa and Bloemfontein; its design doubled the field of good definition (to 8° square) achieved by the Bache astrograph.
191. Thompson (1912).
192. This statement supports the author’s opinion that the success of HCO was not solely built on the leadership of Pickering but benefited significantly from Mina’s input behind the scenes. Paul Kohlmler has presented an interesting case study: ‘Annie Jump Cannon – the most important woman in the History of Astronomy’ (2006) [www.ephemeris.sjaa.net/0612/Cannon.pdf]. However he underestimates the role of her mentor of 15 years and his criteria focus more heavily on her later years, a time when many of the uncertainties of stellar evolution had been resolved. Certainly Cannon became proficient at the rapid classification of stellar spectra, but a quote by Cecilia Payne-Gaposchkin given by Kohlmler (from Greenstein, 1993) is instructive: ‘[Cannon] had amazing visual recall, but it was not based on reasoning. She did not think about the spectra as she classified them ... she simply recognised them.’
193. Hucht, Karel A. van der, ‘The VIIth catalogue of galactic Wolf–Rayet stars’, *New Astronomy Reviews*, 45 (2001), 135–232 gives a total of 227 galactic WR stars. Mina’s 1912 catalogue was the second such catalogue; the first was due to William Wallace Campbell (1862–1938) in 1884 containing 55 stars, 12 of which have since been deleted. Mina listed 94 discoveries of Type V stars (Spectrum O), including 21 within the LMC and 1 in the SMC. Hucht lists 53 discoveries by Mina within the Milky Way. Adding the 22 she found in the LMC and SMC gives Mina a total of 75 WR stars. Among these is the eclipsing binary WR 22 (HD 92740), one of the most massive stars known (>70 solar masses), which she discovered in 1889.
194. 1917AnHar..71..27F, ‘Spectra and Photographic Magnitudes of Stars in Standard Regions’. See also Hoffleit (1991), 140–1.
195. 1912 HCO *Annual Report*, Miscellaneous section.
196. <http://dasch.rc.fas.harvard.edu/project.php> The Plate Store covers the period 1885–1992. See also Sobel (2016), 264–6.
197. Carlisle, Camille M., ‘Flood Threatens Photographic Plates’, *Sky & Telescope*, 2016 March 8. Some 12% of the HCO Plate Store was affected by the flooding. Insurance cover fortunately facilitated a new (faster) scanner and the DASCH project is back on track. In due course this will allow all of the HCO plates that Mina Fleming and her team of computers investigated to be accessed online. In addition a team of volunteers are busy transcribing the individual research journals of the female assistants.
198. ‘DASCH data release 5 (DR5) now available; update on Flood Recovery’, American Astronomical Society, 2016 August 9.

The author

Paul A. Haley was born in 1956 and has lived near Hereford, England, with his wife Ann for the past 26 years. Following a 20-year secondary teaching career he spent eight years delivering astronomy heritage projects across Europe, as director of both The Share Initiative and Space Today UK. Paul is a regular contributor to both the *SHA Bulletin* and *The Antiquarian Astronomer*. Future work will include a new biography of Sir David Gill together with further work on the Wolf–Rayet discoveries of Mina Fleming; design and production of stained-glass panels to commemorate different aspects of the history of astronomy; and further development of Birch Hill Observatory. Paul’s other interests include Pyrenean Mountain dogs and mountaineering.