ISTL Issues in Science and Technology Librarianship

Astronomy's Photographic Glass Plates: Demonstrating Value Through Use Cases

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Abstract

Astronomy's extensive collections of photographic glass plates contain historical images and spectra of celestial objects, documenting more than a century of the observable cosmos. Many reveal changes, both sudden (explosive), periodic, or gradual (evolutionary), which is material of immense interest for time-domain studies because of the long time-base they cover. Those early photographic observations also furnished all the basic data which supported our early understanding of the universe, and from which modern stellar classifications have been derived. Once the ubiquitous workhorse detector, plates or film are now replaced by electronic detectors, and systems are modified to take advantage of advances in telescope technology. This change poses challenges of preservation and accessibility for the plates, leading administrators to question the usefulness of the older materials in relation to the cost of their care and preservation. The following paper details many examples of reusing or re-purposing those plates, demonstrates their unique value to modern astronomy and the history of science, and makes a strong case for committing resources towards their long-term preservation and ultimately their comprehensive digitization.

Keywords: Glass plates, Photography, Archives, Digitization, Astronomy, Astrophysics, Art, Education, Media, History

Recommended Citation:

Whitten, K., Boegen, L., Levine, S., Osborn, W., Griffin, E., Barker, T., Bartlett, J. L., Zrull, L. S., Bouquin, D., & Kern, B. (2024). Astronomy's photographic glass plates: Demonstrating value through use cases. *Issues in Science and Technology Librarianship, 106*. https://doi.org/10.29173/istl2759

Introduction

From the dawn of quantitative astronomy through to the late 1970s, the ubiquitous workhorse detector of professional astronomers was the photographic plate or film. We will refer to those photographic observations as "plates"; they include direct images of objects ("direct plates") and spectra ("spectrograms"), but exclude photographs of objects such as instruments, equipment, people or places. Although plates may contain irreplaceable data, the future of many collections is uncertain. Some remain with the institutions that initially created them, others are transferred to institutional archives, placed in long-term storage, archived at other institutions, or even, in some instances, discarded. This means that not only is locating plates of interest challenging, but gaining physical access to them is also problematic. The metadata necessary to utilize and interpret the plates are usually entered in plate logbooks and/or observers' journals, often (also) written on the envelopes housing the plates and sometimes on the plates themselves but preserving and accessing those items can be difficult. However, despite these and other associated challenges arising from restricted access or insufficient metadata, professional astronomers have continued to make use of, and advocate for, the large reservoir of raw scientific information which plate collections collectively contain. More recently a number of plate collections have been moved out of observatory storage rooms and into their host institutes' libraries. The involvement of librarians and archivists revealed that there is a variety of groups besides professional astronomers and other scientists with interest in the plate collections and asking how this material could be made accessible to all interested communities. Other stakeholders include historians, educators, and those from the arts – writers, artists and the theatrical community.

While the scientific astronomical community is arguably the major stakeholder, another significant stakeholder is historians of astronomy who peruse the older astronomical literature in order to understand how scientific procedures were carried out, how the technology evolved, and whether the hand-written annotations which some plates bear scientific significance. There is tension in the question of preserving or cleaning those annotations, as plate uses and users can have different priorities. While removing annotations that interfere with data may seem the obvious way to go when creating an accurate *digital* record of the plate for scientific purposes, historians find great value in the clues they may also provide to scientific processes and strategies then being employed by scientists. Another important feature of the legacy of a plate archive resides in the storage envelopes, as they often carry scientific metadata and other important notes. We acknowledge that there are conflicting opinions regarding whether, or how, to safeguard those precious aspects of a plate archive, and we plan to address them in the future.

In this paper we highlight other critical stakeholders in this discussion who have a broad range of interests. This includes information about the many alternative uses of these astronomical artifacts by members from other professions, with different interests, who are proficient in assorted specializations quite remote from astronomical sciences. Photographs of the sky record that ephemeral beauty for all time, and the skyscapes and celestial patterns captured on plates have inspired artists across a range of media. Museums may borrow historical plates to give context to stories of discoveries or methodologies. Media outlets popularizing science often request access to photographic plates in order to connect with the scientific culture and practices of earlier eras. As stimuli for new works of art, the interplay of image, glass, and light can be as fascinating as the original views. If artists can gain access to plate collections, past moments of astronomical significance captured on glass will be able to inspire far into the future. In this paper we describe examples of past and recent re-uses of plates in the domain of the arts and humanities, as well as the sciences.

In response to queries and comments from those communities, the International Glass Plates Group (IGPG) (Levine et al., 2022; Long et al., 2021) was formed in 2020 to facilitate interdisciplinary communication, in particular among custodians, librarians, archivists, and users of photographic plates. As a step towards making the plates discoverable and accessible to potential users, we have explored and discussed established current uses, including traditional astronomical studies and other scholarly or popular projects. Given the substantial internal knowledge among the IGPG members concerning scientific and other uses for such plates, plus information readily available through the astronomers' powerful search tool, the ADS (the SAO/NASA Astrophysics Data System), it has been possible to understand the likely range for reusing or re-purposing astronomical photographic plates. The IGPG is now working towards identifying the needs of different users, understanding where the needs may conflict (for example, between scientific use versus historical study), and establishing best practices for the collections. This paper outlines the scope of our enquiries and summarizes the findings both as an initial response to the above-named communities and as a way of establishing a record of the uses of plates.

Astronomical Photography and Plate Archives

The invention of photography in the 19th century heralded astronomy's commencement as a quantitative science. This rich history is traced through the literature with publications produced since the 19th century documenting the use of photography in astronomy from history to discoveries to technical aspects. Examples include Robert Hunt's *A popular treatise on the art of photography : including daguerréotype, and all the new methods of producing pictures by the chemical agency of light* from 1841 and publications produced by the *Eastman Kodak Company including Kodak plates and films for scientific photography* (Eastman Kodak, 1973; Hunt, 1841). Of importance in the literature is proceedings of workshops, which focused on astronomical photography. One in particular, titled *Modern Techniques in Astronomical Photography Proceedings* and held in Geneva in 1978, starts with a very comprehensive article by William Miller, who ran the photo lab in Pasadena that served the then giant observatories in the field, Mount Wilson and Palomar, and was an acclaimed expert (Miller, 1978). A similar workshop was held in 1984 and also focused on astronomical photography that included reports on techniques and methods (Sim & Ishida, 1984). What the relevant literature reflects, and what many astronomers and historians of science know and understand is that with the invention of photography the appearance of objects was no longer dictated by the subjective views of artists or writers. As photographic technology and techniques advanced and evolved, the glass photographic plate became the observing tool of choice. Accordingly, astronomers developed procedures for calibrating the images that permitted the determination of accurate positions ("astrometry"), brightnesses ("photometry"), and features in the spectra ("spectroscopy") of observed objects. These advances permitted the reliable deduction of fundamental astrophysical laws and conditions in space environments.

Decades ahead of the invention of digital methods, plates bearing astronomical observations were carefully stored, and shared when appropriate. The observers thus bequeathed to their successors a double legacy: the science that underpinned astronomy's interpretation of the universe, plus the data with which that underpinning was achieved and understood, the latter generating an archive of unrepeatable observations for potential future discoveries. Given their utility, the plates bearing astronomical observations were carefully stored for reference or later re-study, and much like books in a library they were loaned to interested parties as needed. The result was that many astronomical institutions accumulated tens to thousands of plates. A few of the notable collections of over 100,000 plates are at Harvard University (about 500,000 plates), Carnegie Observatories, Lick Observatory (University of California), Yerkes Observatory (University of Chicago) and the Pisgah Astronomical Research Institute in the US, the Dominion Astrophysical Observatory and University of Toronto in Canada, and Sonneberg Observatory (Germany), Heidelberg University (Germany), the Royal Greenwich Observatory (UK), and l'Observatoire de Haute-Provence (France).

In the late 1970s changes came, and came rapidly, with the invention and introduction of digital cameras. In astronomy the higher sensitivity charged-coupled device (CCD) camera was able to take longer exposures, and exposures of much fainter objects, all with a linear response to the light received, as opposed to the inherent non-linearity of photographic imaging, which quickly led to this technique replacing plate photography as the standard observing method. Those changes seeded gross alterations in the acquisition and storage of astronomical data, and concomitantly general reductions in the management and maintenance of, and access to, plate archives. Despite the large-scale switch to electronic detectors, in many sub-fields photography was far from dead, and we suggest two basic reasons: (A) that photography remained supreme where images of large scale were involved, and (B) that many of the smaller observatories lacked the financial resources to switch completely to the modern electronic detectors and their necessary computer adjuncts. Good examples of developments in photography (rather than CCDs) are collected in the same workshop described early from 1984 with a focus on Astronomical Photography (Sim & Ishida, 1984). Additional literature on this topic that discusses the history and evolution of photographic uses in astronomy including CCD, includes, as an example being G. Wynn-Williams (2016) *Surveying the skies: How astronomers map the universe*.

Even so, the incontrovertible advantage of astronomy's sphotographic heritage is its ability to extend the temporal coverage from modern digital archives that are still relatively recent to a dataset that adds a century or more of observations. Since all celestial objects are changing on some timescale, each observation constitutes a unique and irreplaceable record at a particular time, building a legacy of observations that are invaluable for studying astronomy in the time-domain (i.e., investigating how objects move or change over time). Extracting those time-dependent data is an ongoing quest that demands specialized equipment, funds, and skilled personnel, but it is presently the only route to understanding a considerable subsection of the universe around us without needing to wait another century for today's new data to become old.

It has therefore become imperative to address issues such as preservation and accessibility of plates to redeem matters before degradation of plate collections reaches the point of no return, and this paper is designed to encourage that activity. We outline the current situation and present a wide range of examples in which access to heritage data has proved pivotal. Through this action there must be a balancing of the benefits and the costs of creating correct digital versions of all plates considered worthy of the effort. At the same time, the conflicting perils to astronomy and science of losing such data and material culture altogether must be considered.

Re-Using Plates for Investigations in Astronomy

Among the most frequent uses of astronomy's plate archives are investigations of changes in three measured properties of stars and other cosmic sources: positions, brightness, and radial velocity (i.e., motion along the line of sight). Some representative cases are listed below; a more extensive bibliography of archive mining is given in the Appendix.

Astronomical plates are capable of yielding brightness, position, and radial velocity to precisions and accuracy that are still adequate for modern research and in many instances comparable with what can be achieved with electronic detectors. Specifically, from direct images one may determine brightness to at least 0.10 magnitudes and positions accurate to at least 0.3 arc-seconds, depending of course on the quality of the image and the image scale (Arlot et al., 2018; Cerny et al., 2021; Hippke et al., 2016; Laycock et al., 2010; Osborn, 2000; Robert et al., 2016; Sokolovsky et al., 2017; Thouvenin et al., 2014). High quality spectral plates can yield radial velocities to better than 1 kms-1 (Bychkov, 1987; Griffin, 1973). Uses of astronomy's heritage data also extend to examination of records of one-time events, such as supernova outbursts, as those can be essential for comparison with modern cases as well as for improving and/or confirming past records that may be uncertain.

Since almost all the non-theoretical papers in the astronomical literature published in the early years referred to purposely-acquired observations that were photographic, there is no shortage of examples of quantitative science derived from astronomical plates. From preparing the catalogs used for pointing the Hubble Telescope (finding catalogs) Finding Catalogues' reliance on data measured on photographic plates was ubiquitous and unquestioned. Consequently, the examples described below are merely a tiny representative set and not an exhaustive list. Typical projects include determining binary-star orbits, identifying the precursor to a supernova, and refining the predicted orbit for a newly-discovered solar-system object by measuring its position as observed many years ago. Changes of an evolutionary nature, or describing a long-period effect, can take place in astronomy on timescales that are vastly longer than anything else studied scientifically, barring geology. However, access to a century or more of data is necessary for uncovering and studying long-term effects. If the data are made accessible digitally, and remain available, scientists will be able to ask new questions far into the future.

The following is a very brief selection of time-domain research based on (1) direct sky images and (2) stellar spectra, observed photographically during the 20th century. Two more subsets then follow: sub-section (3) includes examples that specifically involve solar-system studies, while (4) cites some of the instances in which photographic plates were digitized in order to furnish an input catalogue for a space mission or for a specific survey to be carried out with a ground-based telescope. In (5) we have collected a few examples in which plates were consulted in order to confirm some specific events whose reporting was not very precise, and to confirm an intense aurora that was purported to be in recognition of a cultural happening, while (6) records instances of appealing to historical plates in order to correct or extend some possibly misleading information. Sub-section (7) then takes a brief look at ways in which historical spectra have been put to use in other scientific disciplines.

1. Time-Domain Studies Over Long Baselines – Direct Plates

(a). New patterns revealed in stellar variability. The Sonneberg Observatory plate archive contains about 270,000 plates. Three-hundred stars were chosen at random and their images from a 36-year period were compared for brightness variations (Kroll et al., 2000). About 50% of the objects were judged to be variable, some cyclic with periods

over 1,000 days and amplitudes of several tenths of a magnitude and others brightened or faded slowly over decades with smaller ranges. Moreover, a worryingly sizable fraction of the stars designated as photometric constants in the widely-used Hipparcos Catalogue was actually found to be variable on a long timescale.

(b). Discovering new types of variable star by comparing star fields. The Harvard project DASCH (Digital Access to a Sky Century @ Harvard) has created accessible digital copies of the half-million wide-field images in its 100-year archive (Laycock et al., 2010; Tang et al., 2013). It has already proved a significant success, revealing new types of variable stars with much more science emerging as researchers are now able to access the photographic observation online (Tang et al., 2010; Peterson et al., 2019).

(c). Refining the identity of a rare star from light-curves. Burggraf et al. (2015) and Polcaro et al. (2016) constructed light curves showing the brightness changes over the past 100 years for two very luminous blue variable stars in the galaxy M33. From such a broad timespan of data it was possible to unravel more clearly the information regarding the current states of evolution for this very rare type of star.

(d). Testing stellar evolution theory by period changes in pulsating variable stars. Stars evolve as they age, but most changes are much too slow and subtle to be observed directly. They must be calculated from theoretical stellar models. Some stars, however, are predicted to pulsate and consequently vary regularly in brightness with a very precise period. Comparing how a star's period changes from a hundred years or so ago to today provides one of the few direct tests of the theories of advanced stellar evolution (Karmakar et al., 2022; Osborn, 2000; Yacob et al., 2022).

(e). The longest-known eclipsing binary. Eclipsing binaries are orbiting double stars aligned such that one star passes in front of the other as observed from Earth, thereby causing regular dimmings in brightness (eclipses). In 2015 the star denoted TYC 2505-672-1 was discovered to have a very long (3.45 year) eclipse. Review of archived plate studies revealed TYC 2505-672-1 to be the current record-holder (69.1 years) for times between successive eclipses (Osborn & Mills, 2017; Rodriguez et al., 2016), indicating a very widely spaced binary system.

(f). Are quasars variable? Following the recognition in 1963 of the unusual properties of the first-known quasar, 3C 273, the object has been studied in a great many investigations (e.g., Türler et al., 1999) in order to examine the constancy of its brightness and thence to gain a key as to the source(s) of the energy driving such a highly luminous body. No firm consensus was reached. Studying the long-term nature of the variations requires the use of photographic observations, as detailed by Omizzolo et al. (2005) in a study of the quasar 3C345. An investigation by Angione and Smith (1985) involving nearly 1000 photometric measurements - mostly on direct plates but about one-third made photoelectrically - concluded that, while the object varies in brightness, there was no firm evidence of any periodicity. However, the luminosities of other bright quasars have since been confirmed as variable, on timescales ranging from a few hours to a few months.

(g). Photometry of the progenitor of SN 1987A. The progenitor of this event had an unusual spectral type (B3 Ia), so it was all the more important to examine what evidence there was to explain its explosion. The brightness of the progenitor star was measured on a large set of direct plates from the Harvard archive spanning 50 years prior to 1948 (mostly later than 1923), but no changes greater than 0.5 magnitudes were found (Plotkin & Clayton, 2002). That result actually adds more mystery to the event, rather than helping to solve it.

(h). Tightening up the membership of the globular cluster M4. Photographic photometry and proper motions dating back to 1896 (Cudworth & Rees, 1990) enabled membership of M4 to be refined significantly, yielding a tightly-defined color-magnitude diagram, a model of the velocity components, and the identity of new variables.

(i). Resolving a major disagreement over the mass of the bright star Procyon (alpha CMi). Astrometric measurements of double stars enable the masses of the two stellar components to be determined. Embarrassingly, for many years the derived mass of the brighter component of the Procyon system seemed to be in serious disagreement with the predictions of theories of stellar evolution. Since the orbit has a period of 40 years, it is necessary to prepare a database that is long enough to include several cycles. Thus, a re-determination of the orbit (Girard et al., 2000) that combined accurate observations by the Hubble Space Telescope with hundreds of plate observations that covered the orbit back to 1912, resolved the discrepancy by demonstrating that the orbital solutions in the earlier literature were in error.

(j). Historical outbursts in an X-Ray binary. Photographic magnitudes for the X-ray binary A0538-66 were measured on 91 plates from the Harvard archive and indicated modulations in the periodicity of cyclic events; they were marked around the ephemeris maximum but failed to show at all in some other phases (Brock et al., 2002). That behavior seemed to echo what has been re-observed since. Even when armed with more recently-derived parameters, researchers still find the true nature of the system puzzling.

2. Time-Domain Studies - Spectra

Astronomical observing is usually thought of in terms of direct imaging, but that is far from reality. As Robbins and Osborn (2009) showed, large fractions of our plate archives are of spectra, which are most commonly employed to measure detailed properties (such as chemical composition and radial velocities) of stars, galaxies, and other celestial objects, and to investigate changes in those properties.

The observing instrument is the spectrometer, which incorporates either a prism or a diffraction grating to disperse light into its constituent rainbow (spectrum) of colors. If the observation includes the visible range of wavelengths, they can be perceived by the human eye as extending from violet to red (or some portion of that, depending on the equipment used). The spectrum can be photographed (usually in black and white). However, because light is composed of electromagnetic waves of different wavelengths, it is better to define a spectrum as the relative brightness of the observed light as a function of wavelength, rather than in terms of non-quantitative, and somewhat personal, descriptions of color as perceived by individual people. One can then describe the features of a spectrum accurately and objectively.

An atom, ion, or molecule both radiates and absorbs light at wavelengths that are uniquely specific and constant. In the case of a star, for example, the outer, cooler, atmosphere absorbs energy being emitted from hotter interior regions, giving rise to dark features that correspond precisely to the wavelengths characteristic of the atom, ion or molecule responsible for the absorption. The positions of those dark features thus reveal unequivocally the identity and abundance of the element responsible (and reveal much, much more besides). Measurements of the wavelengths of the features in the observed spectrum compared to their laboratory wavelengths indicate directly the radial velocity of the source (in this case, the star).

(a). Radial-velocity measurements reveal stellar multiplicity. Periodic changes in stellar velocities indicate that a star is in a binary orbit. These programs were very common in the early 20th century as little was known initially about stellar multiplicity. When periods are several years long, recourse to older measurements substantially helps to refine an orbit. To assist other users, many catalogs have been compiled (e.g., Batten et al., 1989). Results from such programs established that well over 25% of stars in our Galaxy are in multiple star systems. The early journals contain numerous "discovery" papers of the binary nature of even bright stars.

(b). Basic properties of stars. Images of the spectra of stars enabled trained employees (women "computers") at Harvard College Observatory to classify the spectral types of a quarter of a million stars; they published them in the Henry Draper Catalogue between 1918−1924 (e.g., Cannon & Pickering, 1918). The observations were akin to direct plates, but with a prism inserted into the optics such that each direct stellar image was converted into a spectrum. Those "HD" classifications are a mainstay for modern astrophysics, as essential now as they were in the early 20th century and used widely in statistical work.

(c). Ratios of the masses of binary-star components. Certain categories of binary orbits can yield ratios of the masses of their component stars. The orbits may often be improved substantially if archived data can be included (e.g., Griffin et al., 1990; Griffin et al., 1993; Griffin & Griffin, 2000). This is a precious opportunity to derive unique science; the results also offer a valuable test of theories of stellar evolution.

(d). Persistent and phase-dependent spectral features. Archived spectra observed photographically during the 1956 and 1983 eclipses of the long-period enigmatic star ε Aurigae (Griffin & Stencel, 2013) were digitized and combined with modern CCD ones observed during the 2010 eclipse in order to determine which of the subtle spectroscopic changes that occur during the near-total eclipse recurred and which (if any) were serendipitous. This test had not been attempted before, and it yielded results that challenged all the models. Its eclipse appears to be a unique phenomenon, as the companion object cannot be fully star-like.

(e). Looking closely into eruptions in dwarf novae. Examination of spectra accompanying eruptions in objects known as dwarf novae (e.g., Schaefer et al., 2022) offers unique

opportunities to determine and trace the cause(s) of the eruptions and the mechanics of what happens. Dwarf novae are the less energetic versions of classical novae; both types have been very popular observing targets for decades, and the literature is brimming with examples, both ancient and modern. Both types are also highly popular with amateur astronomers, who always hope to observe something rare or special. Amateurs usually share their data with the AAVSO (American Association of Variable Star Observers), which holds databases of many thousands of professionally vetted photometric measurements and numerous spectra.

(f). Observing a final "helium flash" in an expiring star. The irreversible changes, including dramatic mass-loss, that occur as a star finally evolves towards its late-stage lifetime as a white dwarf, are rare to see, and impossible to predict. Observations of those final bursts of life are therefore extremely precious, but with luck they can sometimes be caught by mining an appropriate archive, as did Clayton and De Marco (1997).

(g). The unique potential of measuring a "chromospheric" eclipse. If an eclipsing binary star system consists of a cool giant and a hot dwarf, the dwarf will shine through the atmosphere (technically, the chromosphere) of the giant primary just before, and just after, it is eclipsed by the primary. The dwarf's light thus samples the physical and chemical properties of that chromosphere at a sequence of heights. These events are rare (less than 10 such systems bright enough for detailed study are known). As described by Griffin and Ake (2015), full quantitative analyses of those chromospheric lines are the only way to derive reliable information about a giant's chromosphere without highly specialized equipment.

(h). Spectra changes in a semi-regular variable. The star WZ Cassiopeia is a cool red giant whose brightness varies over about 2.5 magnitudes in separate periods of 6 and 12 months. Molecular bands that were observed in its spectrum to be very strong in 1958 had disappeared by 1974 (Keenan & Bidelman, 1979). More observations to back up the historical one will help to elucidate the nature of such stars.

(i). Changes in emission or absorption features in very young stars. T Tauri stars are young objects in the late stages of formation. Both short- and long-term changes in spectral lines are noted; eclipses are also seen but can commence or cease abruptly. Causes could be intrinsic or extrinsic, or both; accretion, wind, and dust are probably involved. Mining plate archives has turned up valuable evidence of eclipses and other changes in the past (Beck & Simon, 2001; Winn et al., 2003), demonstrating that individual examples are plentiful but diverse. None is fully understood.

(j). The conundrum that is HD 108. This 7th-magnitude O-type star is so rare as to be almost unique. As described by Nazé et al. (2001), 20 recent years of CCD spectra showed how its spectrum changes irregularly, primarily through strengths in both emission and absorption in He I and He II, while some Balmer lines also vary from pure absorption to P-Cygni profiles (closely adjacent emission and absorption components indicative of outflowing material). Nazé et al. (2006) were then able to investigate the object on archived plates dating back to 1950 and measured its spectrum line-widths and radial velocities. The period, though imprecise, appeared to be 50 to 60 years;

additional aperiodicities could be ascribed to profile changes, possibly attributable to stellar winds.

3. Time-Domain Studies – Solar-System Objects

(a). Members both distant and faint. Small bodies that belong to the Kuiper Belt − the outermost region of the solar system and populated by thousands of small icy objects, the largest being the dwarf planet Pluto − are difficult to detect. Discoveries are still being made, and recourse to archives of direct images is key to many such discoveries, largely on account of the long time-base which is represented and therefore the large arc which the objects traced against the stellar background. Quite recently a large KB object (Quaoar) was spotted during a KBO search program (Trujillo & Brown, 2003); it was found again on earlier images of the program, confirmed by examining a high-resolution photographic image from 1983, and its orbit determined precisely by measuring another high-resolution plate from 1954. Only when a substantially representative sample of these objects have been identified and characterized can we determine with any certainty how the Kuiper Belt originated, and thence how the solar system began its evolution into what it is today.

(b). Understanding comets. The discovery and science of comets is also of considerable interest; some are one-time visitors, their orbits having been deflected by the gravitational tug of a solar-system planet. The evidence which they display can also bear upon theories of the formation of the solar system and of the Earth itself, as Pinto et al. (2022) showed.

(c). The search for potentially hazardous asteroids. Of great concern is the risk of the collision of the Earth with a body moving through the solar system large enough to cause significant damage to the Earth. Finding and determining the orbits of these "Near Earth Objects" (NEOs) is the focus of a NASA campaign to identify such wanderers, and again recourse to old images is crucial for refining the orbit of what the modern (but necessarily brief) observations may suggest is an NEO.

4. Compiling Basic Catalogues and Use of Plates in Support of Space Missions

Accurate positions from measures on photographic plates can be applied to support space missions. For example:

(a). Improving the closest approach data for the 2015 flyby of Pluto. In preparation for the 2015 New Horizons reconnaissance flyby study of Pluto and its moons, over 800 photographic plates of Pluto taken between 1930 and 1951 were digitized and measured to support and improve the spacecraft's navigation to closest approach (Buie & Folkner, 2015).

(b). Serendipitous use of the Hubble Space Telescope Guide Star Catalogue. The Palomar Observatory Sky Survey plates (POSS) (Minkowski & Abell, 1963; Reid et al., 1991) were digitized to create the input catalogue for aiming the Hubble Space Telescope. The digital images data were subsequently made available online as the Digital Sky Survey

(DSS) (Lasker, 1995). The tremendous number and assortment of applications of the DSS for thousands of projects by researchers and the general public interest demonstrates the huge potential and practical value of astronomy's plate legacy observations once digitized and readily accessible. One example of recent research utilizing visual inspection of parts of the DSS is the unexpected discovery of new galactic star clusters (Casado, 2021).

5. Records of One-Time Events

As well as providing irreplaceable input for time-domain studies, plate archives often contain the only reliable means to re-study events occurring in the years prior to digital imaging for comparison to more recently observed cases. Observations of novae and supernovae outbursts and of historic comets are typical uses. Occasionally the plates also have non-astronomical uses.

(a). New light curve for an unusual nova. Luberda and Osborn (2012) combined published observations of the 1909 outburst of the unusual nova RT Serpentis with new measurements made on archived plates and were able to derive a light-curve on the modern photometric system used for nova observations today.

(b). Confirmation of a reported nova in 1437 AD. One of the oldest astronomical events to be confirmed via plates is a nova recorded by the Korean royal astronomers in 1437 (Guarino, 2017; Shara et al., 2017). Recent efforts were able to locate the associated white dwarf star and its erupted shell on plates from 1919 to 1951, and thereby confirmed the nova record that was over 580 years old.

(c). Meteor observations. The brightness of many historic meteor observations was determined from observations of the meteor on photographic plates. Andreic et al. (2019) discuss how the old "photographic meteor magnitudes" have research value once transformed to the modern meteor brightness system.

(d). Native American oral history. Plates can confirm historic cultural events. Black Elk, an Oglala Lakota (Sioux) holy man, prophesied that God would provide some sign upon his death. Lakota oral tradition relates that on the night he died (August 19, 1950) there was a spectacular auroral display. Archived photographic plates confirm that a very bright aurora was indeed visible over most of the northern hemisphere on that date (Hollabaugh, 2019).

6. Correcting or Completing Astronomical Information

Examining the original plates is sometimes the only way to confirm a past observation and render it of more use today. Researchers might also identify errors in published data and thereby explain puzzling observations.

(a). Cross-indexing early variable star observations. Examining the original plate is sometimes the only way to confirm a past observation and make use of it today. For example, between 1925 − 1931 astronomer Frank Ross published several lists of new variable stars but gave only rough positions for them. By reviewing the same plates and

Ross's annotations, and by cross-indexing, Osborn and Mills (2011; 2012) determined accurate positions for the stars and in some cases extended their light-curves back in time.

(b). Resolving a problem with the Catalogue of Carbon stars. Carbon stars are an important, and fairly rare, type of star. The General Catalogue of Cool Carbon Stars (Stephenson, 1989) contains a list of nearly 6,000 entries but unfortunately it also contains errors and omissions. By examining the original plates it was possible to correct poor or erroneous positions, and thus to recover "lost" stars that could not otherwise be located (MacConnell & Osborn, 2005; Osborn et al., 2005).

(c). Confirming suspected comets. The Cometography project (Kronk et al., 2017) is a multi-volume compendium containing information on all comets ever observed. The final work is now dealing with previously reported but unconfirmed observations. The original plates for those that were reported from photographic observations are being used to corroborate or disprove the observations and in some cases to derive orbits (e.g., Green, 2023).

Scientific Applications in Related Disciplines

We now examine some of the multiplicity of ways in which astronomy's historical archives of photographic observations can support scientific investigations in disciplines allied to, but not identified as, astronomy. While astronomy represents the *primary* modern scientific use of historical plates, these records are also of value in other related disciplines as instanced below.

(a). Atmospheric science. Every observation of a celestial object made from the ground must pass through the Earth's atmosphere, and in so doing it will unavoidably carry evidence of the materials in that atmosphere. One atmospheric constituent that is of vital importance to all living organisms on the Earth is ozone; it is present in only very small amounts - the equivalent, at standard temperature and pressure, of a layer only 3 mm thick. Monitoring the thickness of the ozone layer did not commence until 1926, at a mountain site in Switzerland, and for a number of years those measurements were only of experimental quality. It has since become critically important to discover whether the average concentration of ozone was constant until anthropogenic influences (in the form of CFCs) appeared to start destroying it, or whether it undergoes periodic or other variations on its own. The only known sources of data that could supplement the Swiss ones are astronomy's spectrograms of hot stars. In a unique research project Griffin (2005; 2006) and Griffin et al. (2006) isolated and analyzed the ozone features produced by the Earth's atmosphere in order to measure the abundance of stratospheric ozone in those early years when it was not measured very adequately from the ground.

(b). SETI (Search for Extra-Terrestrial Intelligence). Another possible re-purposing of plates has been identified by SETI advocates. Villarroel et al. (2022) have suggested that evidence for extraterrestrial life might be found by searching for Earth-orbiting space items on plates exposed in pre-Sputnik years. In those years, interstellar and interplanetary space was free of space debris – the pieces of (mostly unidentified) junk

discarded by spacecraft and their rockets. Near-Earth space is now so cluttered it would be extremely difficult to carry out such a search.

Training in Skills and Methods

Plates are remarkable tools for teaching both students and professional astronomers techniques for working with historical data, and applying their findings to contemporary research questions.

(a) As a general introduction to research, a recent program at Yerkes Observatory (WI) partnered high school students with professional astronomers (for one example, see https://glaseducation.org/mcquown-scholars/) in time-domain research projects that made use of plates (Gollapudy & Osborn, 2019).

(b) Plates can also be used to train practicing astronomers. The training lies in judging how likely an old-technology observation will compensate for its lower quality resulting largely from the inferior DQE (detective quantum efficiency) of a photographic emulsion compared to a CCD. For instance, the Gaia mission, launched by the European Space Agency in 2013, records data – both direct images and spectra − of stars in the Milky Way. Some of the spectra produced by Gaia are very similar to the low-dispersion spectra such as those obtained with objective-prism plates. An objective-prism spectrograph combines a conventional direct observation with spectroscopy, by means of a prism placed in front of the telescope, usually just in front of a Schmidt telescope's corrector lens. Thus, each individual circular star image is converted into a band that is its spectrum. But objective-prism plates were rarely used after about 1980, meaning that by 2013 most astronomers had neither the experience nor the necessary skills for interpreting those low-dispersion spectra. During the development of artificial intelligence and machine-learning techniques to manage the Gaia spectra, assorted objective-prism plates were therefore employed to simulate the Gaia observations and to orient astronomers unfamiliar with their characteristics (Hudec & Hudec, 2011).

General Education and Science History

Besides the uses favored by historians, exhibitions sometimes utilize plates to give context to stories of discoveries or methodologies. Media outlets popularizing science use plates to connect with the scientific culture and practices of earlier eras. Furthermore, if the plates remain available and accessible, people ask new questions of these artefacts that relate to the future, thereby continuing to grow our understanding and appreciation of the history of science. This section offers some examples of reusing or re-purposing plates by historians and educators.

Teaching: Formal Education

(a). Plates taken for astronomical purposes are often sought out for primary and secondary education. Examples include K-12 astronomy education courses (e.g., Pompea & Blurton, 1998; Sadler & Luzader, 1990; Sunal & Demchik, 1985) and online learning tools (for example, by the Pisgah Astronomical Research Institute, https://www.pari.edu), while BBC Scotland developed an online children's course about astronomer Williamina Fleming and her critical contribution in classifying the Harvard plates (BBC Scotland, 2019). More recently examples include a collection of resources for middle and high school teachers on Henrietta Swan Leavitt, which includes some plates in some of the biographical videos (Project PHaEDRA, 2018), curriculum material on Williamina Fleming for middle and high school students from PBS, which include representation of plates in the video (PBS, 2020), and online resources for curriculum use by Slooh that uses plates to talk about Pluto's discovery (Slooh, n.d).

(b). Plates are also used in higher education, supporting PhD dissertations and theses and university courses, including the following examples:

- Hubble's *VAR!* plate is a part of the curriculum for Astronomy and Astrophysics II, taught at the University of Heidelberg, Germany. When compared to previous observations of the same region, the VAR! plate represents the first documentation of a Cepheid variable. Calculations of the Cepheid on both this and other plates established the fact that many of the objects seen in our night sky are actually located beyond our Milky Way galaxy (information shared with Whitten, personal communication, March 7, 2022).

- *Mapping the heavens: Early astronomical surveys* is offered at the University of Chicago R. Kron, cross-listed between Astronomy & Astrophysics, and History, Philosophy, & Social Studies. Students recreate Hubble's PhD dissertation work using the plates he took at Yerkes Observatory in 1917. The broad recognition of Hubble and his scientific impact on our understanding of the size and characteristics of the Universe encourages non-Astronomy and Astrophysics majors to enroll and fulfill a general education credit (information shared with Boegen, personal communication, January 10, 2022).
- *Starstruck! The history, culture, and politics of American astronomy*, a course listed by the Department of the History of Science at Harvard University, focuses on the history of American astronomy via material culture. It also features a visit to Harvard's plate archive (Schechner, 2020).

Teaching: The Public Domain

Public programs and publications have drawn importantly from plates to bring astronomy to the public beyond formal teaching. At the turn of the 20th century, photography that employed glass plates held the public's fascination. Sharing actual images was not possible until the advent of photography, so until the late 19th century, the announcements, and discoveries which observational astronomers reported were relayed to the public as hand-drawn replicas, i.e., in the mode in which they had been copied from the telescope's eyepiece. In this matter, the public relied totally on an astronomer's full objectivity, as well as innate persistence and artistic ability, to back up an announcement truthfully with freehand drawings of objects like lunar landscapes, faint nebulae, or planetary rings (Nasim, 2013). Unfortunately, absence of subjectivity could never be guaranteed – and indeed Herschel, the master telescope builder and observer, regularly delighted readers with tales of circuses (cities) on the Moon, but which were actually the product of an overly-fertile imagination coupled with an insatiable curiosity to see such edifices. Lowell was another observer who became convinced that the planet Mars was criss-crossed by channels, or canals, but finely-resolved photographs, backed up by observations with larger telescopes, disproved the notion.

The advent of the photographic plate introduced a revolutionary reduction of such subjectivity and introduced a change that made astronomical images accessible world-wide, able to be copied and shared, and also placed observational astronomy on a more faithful and honest footing. This improved practice quickly opened up a new visibility for the night sky – the ability to share real science that had the potential to capture the imaginations of people everywhere. As astronomer Allan Sandage once remarked, "Astronomy is everybody's second science ... it's the general public's escape. Astronomy sells to the general public, all the time. I think people are just innately interested in it." (Wright, 2021). From museums and planetariums to films and books, whether in studies of history or as figments – sometimes realistic, sometimes exotic − of the imagination, plates have been instrumental in conveying ideas and excitement, as well as sharing plain evidence, to students of public education programs and projects everywhere.

Programs

(a). The first modern planetarium began regular operation in 1925, bringing the sky closer to audiences than ever before. Modern planetarium programs, for example like the Adler Planetarium's *Imagine the Moon* held in 2018, can now incorporate both plates and full-color digital images, to create irreplicable, immersive experiences (Adler Planetarium, 2018).

(b). Images from plates have sometimes been on display at international exhibitions and World's Fairs. For example, the 1930 Golden Gate Exhibition featured a 4 x 10-foot mural of plates from Mount Wilson in an exhibit, *Science in the Service of man* (Meyer, 1939).

(c). Uses of plates in public programs extend beyond the precinct of astronomy or science-focused education. The Driehaus Museum hosted a program called *Out of this world* on May 19, 2022, which included planetary imaging that used astronomical plates (*inter alia*) to explore the cosmos as a source of fascination, influence, and exploration across art and science during the late 19th and early 20th centuries (Driehaus Museum, 2022).

Publications

Historians of science use plate images in books and articles to illustrate the history of science and humankind's understanding of the universe.

(a). Both the images and physical attributes of plates are particularly important to the study of the history of visualization, imagery, and photography, in science (Nasim, 2019).

(b). A recent popular history of science publication was *The glass universe* (Sobel, 2016), the true story about the "women computers" (low-paid but trained women employees) at Harvard. Sobel spent many months visiting Harvard's plate collection, using the plates partly as visual aids, but also to gain a better understanding of the level of science that women were carrying out in the late 19th and early 20th centuries.

(c). The Lick Observatory plate archive played an important role in preparing the definitive biography of E. E. Barnard, *The immortal fire within: The life and work of Edward Emerson Barnard* (Sheehan, 1995).

(d). The author of *Hubble, Humason and the Big Bang: The race to uncover the expanding universe* (Voller, 2021) used Carnegie Observatories plates to research the scientific partnership between the astronomers featured therein.

(e). In *Psychological testing manual: Basic concepts in psychological testing* (Meier, 2021), drawings of Saturn based on telescope observations in the early 1600s, a plate of Saturn taken in 1943, and a 2004 photo of Saturn's rings taken by the Cassini space probe are juxtaposed to support the argument that, as "science matures, improvements in measurement methodologies should lead to advances in theory and research."

(f). Authors of children's books, too, have appealed to astronomical plates for their research. A recent example is *She caught the light: Williamina Stevens Fleming, astronomer* (Lasky, 2021).

News and Entertainment

Much of the public's current interaction with astronomical imagery comes via audio-visual mass media such as television programs, stage productions, podcasts, films, and videos. In these applications, as in other instances that serve the general public, uses of plates span a very wide range, whether to teach principles of astronomy, to provide historically accurate images of the night sky, to tell the stories of those who observed and researched with the plates, or simply to inspire and induce awe. Just as scans of documents, portraits of people, and pictures of places are used to illustrate and inform news and entertainment related to art or social and political history, plates can serve the same purposes. As examples we cite:

(a). NASA Astronomy Picture of the Day titled *Edwin Hubble discovers the universe* for April 26, 2020 (NASA, 2020)

(b). PBS Breakthrough series episode in 2019 entitled *Telescopes* (PBS, 2019)

(c). TED talk *A stellar history of modern astronomy* given by Emily Levesque (Levesque, 2020)

(d). The stage play, *Silent sky* (Gunderson, 2015)

(e). The YouTube episode by Physics Girl called *The sky in 350 billion years* (Physics Girl, 2021)

Museum Exhibits and Art

Museums use plates in both science and art-focused exhibits. Artists respond to the scientific, historic, and material stories of plates. Including plates in exhibitions about contemporary astronomy lends context to stories of discovery or methodology. There appears to be no limit to the different ways astronomy's historical imagery inspires artists, demonstrating beyond question the artistic value that plates may impart, quite aside from their scientific or historical context.

Museum Exhibits

(a). In 2018, the London Science Museum borrowed several of Harvard's spectrograms featuring Payne-Gaposchkin's research annotations. The aim was to help educate the public about the Sun in their exhibit, *The Sun: Living with our star* (London Science Museum, 2018).

(b). In 2023, the Smithsonian Museum of Natural History opened an exhibit based on light pollution which will feature several plates (Smithsonian Museum of Natural History, 2023).

(c). The Adler Planetarium incorporated plates in *What is a planet?*, its 2015 exhibit about Pluto (Adler Planetarium, 2015).

(d). Harvard's Collection of Historical Scientific Instruments included plates in their 2017 exhibit, *Scale: A matter of perspective* (Harvard Museums of Science & Culture, 2017).

Astronomical Plates Inspiring Art

(a). It is difficult to argue that action painter Jackson Pollock's *Comet* displayed at the Wilhelm Hack Museum, Ludwigshafen, Germany in 1947 and *Galaxy* displayed at the Joslyn Art Museum, Nebraska, USA, in 1947 were not influenced by the artist's interaction with astronomical images from plates exhibited at MoMA (Anfam, 2015).

(b). In 2019, artists at The Lapis Press in Culver City (CA) used Carnegie Observatories' plate archive as a resource for creative projects. One of the outcomes, a photographic series called *Boxes*, was on display at the Lapis Press in the early 2020 and is now in the collection of the Los Angeles County Museum of Art (Brandt, 2020).

(c). Plates from the Yerkes Observatory archive was used to print cyanotypes on site in the Yerkes Observatory darkroom; the artist then bound the prints into a book (now held in a private collection). Imagery from this project was a runner up in the audience favorite category in a campus-wide University of Chicago "Science as Art" competition in 2022, while a piece that incorporated Plate 8 from Barnard's *Photographic atlas of selected regions of the Milky Way* was a Judges' Honorable Mention (Lerner, 2022).

(d). *Tracing luminaries* honors the work of Harvard's women computers. The ink annotations of what is often identified as the women's analysis, measurements, and computations remain on many plates, which artist Erika Blumenfeld copies in gold to illustrate their important scientific contributions (Blumenfeld, 2022).

(e). *Measure*, an exhibition examining the work of astronomer Henrietta Leavitt, included quilted artwork and hand-sketched copies of plates. Measure was created by Anna Von Mertens and displayed at the Radcliffe Institute in 2018 among other locations (Von Mertens, 2018).

(f). Mount Wilson Observatory and Carnegies Observatories collaborated with the Los Angeles County Museum of Art's Art+Technology Lab and presented *Standard candle* by Sarah Rosalena which was on display in 2023. *Standard candle* featured a series of woven and beaded textiles made using computer code and is based on archival glass plates captured by Mount Wilson's 100-inch Hooker telescope. The exhibition was organized around a body of work developed by the artist in response to the labor of female "computers" — women who worked at the observatories at the turn of the 20th century (Rosalena, 2023).

(g). In 2015, a cyanotype artist Lia Halloran, spent several weeks at the Harvard Observatory studying plates for a series that would later become *Your body is a space that sees* (Halloran, 2015). It has been on display in numerous locations, including the Los Angeles airport. The artist also took inspiration from the solar plate archive at Carnegie Observatories to create *The sun burns my eyes like moons*, on display in Summer 2021 at the Luis De Jesus Los Angeles gallery (Halloran, 2021).

Literature on Photographic Plates

The use of archived photographic plates in some fields of modern astronomical research is well documented. Robbins & Osborn (2009) have given a list of research papers which involve the use of plates, and which were published in major astronomy journals during 2000−2009. Only papers that specifically focused on astronomical research projects were included; papers such as reports on tests of digitization techniques or descriptions of the contents of plate archives were omitted. Thus, the actual number of papers dealing with astronomical plates in that time period is well under-counted.

The 2009 list of publications dealing with astronomical plates is extended in this paper to 2022 and provided in the Appendix. A few classic papers published before 2009 are included.

This list is divided into four types of references:

- Overviews: articles and conference summaries related to astronomical plates in general
- Research papers: papers that appeared in peer-reviewed journals reporting astronomical research that made use of plates
- Non-research papers: articles and reports on plate-related topics that are not directly related to basic astronomical research. Examples are reports on existing

plate archives, on measuring and digitization tests, scanning programs, and articles and commentaries on plate preservation, plate handling and plate use in general.

- Other plate-related references: Brief notes or abstracts of papers presented at conferences; notes and minutes from conferences or working groups.

Conclusion

Throughout this initiative to amass examples of the analysis and application of astronomy's historical glass plates, two points have become clear. The first, and most obvious, is that archives of astronomical material are highly valuable from a scientific point of view. The second is that these archived materials can have considerable potential for re-purposing in areas that were not – often, could never have been − anticipated by their creators.

As evidenced in this paper, astronomers, earth scientists, historians, educators, media representatives, and artists can attest to the importance of astronomical plates in the 21st century. Some examples require the plates to remain artefacts frozen in time and with any annotations intact; others require annotations to be cleaned away. Some examples can be transformed adequately by a digital representation of the plates; others will continue to require physical access. Even where digitization can be carried out sufficiently with modern machines, the need may arise for new versions as digitization methods and technologies evolve. However, caution is needed, as the volumes and labor not only of working with new technologies but also of managing all the individual calibrations (photometric and astrometric for direct images, and in intensity and wavelength for spectra) that would be required again, will be very substantial.

This paper establishes the recent uses of astronomical photographic plates. The custodians of plate collections should keep the above variety of uses in mind when making decisions about the conservation and promotion of their materials and involve specialists and experts from appropriate disciplines as advisors or referees. For example, it is critical to recognize that digitization that may be unnecessarily fine for one purpose can always be degraded, but the converse is never true. Astronomical photographic plates are an essential resource, for both scientific and cultural uses. A sustainable and ongoing plan to preserve plates correctly and make them widely accessible is critical. They are an important resource that should not be lost to time.

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Appendix

Published material related to astronomical photographic plates: 2009 - 2022

Compiled by:
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Listed below is a representative selection of publications dealing with astronomical photographic plates that appeared in the period 2009-2022. A few classic papers published before 2009 are included. It was unrealistic to carry out a systematic review all of the astronomical literature over the past fourteen years. Thus, this list should not be considered comprehensive as there are certainly some omissions.

The list is divided, somewhat arbitrarily, into four types of references:

- Overviews: articles and conference summaries related to astronomical plates in general
- Research papers: papers that appeared in peer-reviewed journals reporting astronomical research that made use of plates
- Non-research papers: articles and reports on plate-related topics that are not directly related to basic astronomical research. Examples are reports on existing plate archives, on measuring and digitization tests, on scanning programs and articles and commentaries on plate preservation, plate handling and plate use in general
- Other plate-related references: Brief notes or abstracts of papers presented at conferences, notes and minutes from conferences or working groups

Overviews

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