

Integrating Advanced Imaging of Astronomical Glass Plates

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Abstract

The Harvard Plate Stacks (HPS) Astronomical Photographic Glass Plate Collection comprises over 600,000 glass plate negatives. To support collection preservation and improve accessibility, HPS integrated an advanced imaging system to digitize astronomical features in the emulsion layer, as well as annotations made by pioneering Women Astronomical Computers in the late 19th and early 20th centuries. HPS installed a multispectral imaging system to capture high-quality images of astronomical features dating back to the 1880s, along with their historical annotation, to advance both astronomical and cultural heritage research. This digitization of glass plate negatives builds upon 20 years of advanced imaging methodologies and technologies, using the latest equipment and workflows. This includes new post-processing techniques, data management, and workflows across discipline boundaries by a collaborative team.

Early Astrophotography and Historic Datasets

The HPS glass plates collection is the world's largest single holding of historical images of stars, galaxies, and space, consisting of over 600,000 glass plates taken worldwide from the 1870s through the 1980s. These plates comprise humanity's first systematic photograph of the visible universe, taken thousands of times over, with the longest stretch of historical data on the universe accessible to the public [1]. In addition to this important astronomical record, it also provides a historical record of humanity's growing knowledge of the universe and early photographic methods for calculating key information, such as an astronomical object's position, brightness, and composition.

In 1877, Edward Charles Pickering became the fourth director of the Harvard College Observatory (HCO). Aware of the Observatory's early experimentation with astrophotography, Pickering's primary interest as director was in establishing a photography program that would build a large-scale resource of astronomical images covering the northern and southern hemisphere skies many times over. By the 1880s, Pickering had sourced funding for this work from Mary Anna Palmer Draper, the scientific collaborator and widow of photography pioneer and amateur astronomer Henry Draper. Harvard's photography program would produce the Henry Draper Memorial, a catalog of stars classified by their stellar spectra named in memory of Mrs. Draper's late husband. Additionally, her funds would support the systematic, repeated photographing of the entire night sky to build a dataset of images containing stars and objects to the fourteenth magnitude [2].

Data, and what we now call metadata, was recorded during the entire lifecycle of the image from shipping and receiving to capture and analysis. Commercial glass plate negatives were delivered to Cambridge, MA, and then shipped across the globe to Harvard's network of telescopes. With observatories from California to Peru, this included valuable transit information and material characteristics such as plate manufacturer and emulsion type. At the telescope, the observer would record detailed information including

the assigned plate ID, target object, celestial coordinates, exposure length, sky conditions, the observer's name, and any remarks about the capture, such as plates being discarded or used for focus. In an observation logbook the observer would also record details about the telescope itself, including its aperture, focal length, lens type, and geographical location (Fig. 1).

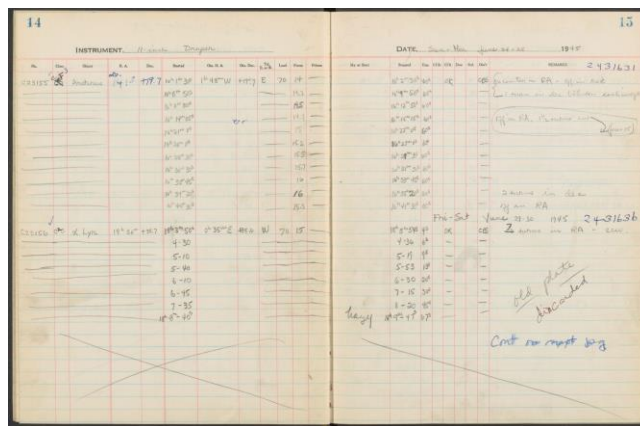


Figure 1 11" Draper Telescope observation logbook. C plates, Book 55, pages 14-15. Harvard Plate Stacks collection.

The observatory's darkroom attendant developed the exposed glass plate negative, then the Women Astronomical Computers assigned a quality number and cataloged it into the collection. It was then available for analysis by the many Women Astronomical Computers on staff at the Observatory.

During this time, Pickering writes at length in the Harvard College Observatory's Annals and Circulars about the prolific volume of data gleaned from the collection and the new challenges and opportunities it presented. In a Circular from 1907, Pickering details the problem of access to the photographic information being accumulated across observatories and in amateur collections worldwide. He explains the need for a published record documenting where collections of astrophotographs are held, along with a list of accessible images and their essential data to determine if they contain the information one requires for one's research. [3]

Women Astronomical Computers

Women were trusted, though mostly uncompensated, administrators and research assistants at the HCO starting as early as the 1870s. Pickering knew that building a comprehensive dataset of the visible Universe would require a team of skilled workers to extract as much usable information as possible from the thousands of photographic plates. While generous, Mrs. Draper's funds were not unlimited, so, starting in the 1880s, Pickering chose to recruit a team of women whom he could pay at a fraction of what he would have paid men for similar work. Among these women was

Williamina Fleming, a Scottish immigrant and single mother who would become one of the most famous women astronomers of her day. Fleming was employed as a housemaid in the director's mansion in 1878 and, in 1881, was recruited to work as an astronomical computer at the observatory. Over the next two decades, Fleming was promoted to manage the team of Women Computers, ran the publication of the *Annals*, developed the first iterations of the Harvard spectral classification scheme, and in 1899 received the title of Curator of Astronomical Photographs, becoming the first woman to have an official appointment by the Harvard Corporation.[4]

Over 150 women would follow in Fleming's footsteps at the HCO, from Henrietta Leavitt, whose work on variable stars allows astronomers to measure distance in space, to Annie Jump Cannon, who classified over 200,000 stars for the Henry Draper Memorial catalog of stellar spectra, to less-known names like Sarah Frances Whiting, an accomplished educator who started the astronomy program at Wellesley College where many generations of women astronomers have studied and still do today. [5]

Pickering directed the Women Computers to perform various tasks and projects, including photometry and spectroscopy. Photometry involved determining differences in the brightness of stars that appear roughly the size of a grain of pepper on the glass. These Women Computers had to find Standard stars, meaning ones that did not vary in brightness, as reference points, and differences in telescopes, exposure lengths, emulsion types, and other factors had to be taken into account when determining a star's magnitude. Many measurements across many photographs had to be taken before designating a star's magnitude. With spectroscopy, Women Computers studied photographic plates made with a prism or grating in the telescope, which dispersed a star's light into a spectrum, allowing them to analyze its colors and patterns rather than a single point of light. They would observe this spectrum, sometimes as small as a grain of rice, noting patterns in their absorption and emission lines to then assign an appropriate stellar category.

In the course of this work, they would annotate the glass side of the plate with a fountain pen while making detailed notes in a corresponding notebook. Much of the glass plate annotations and notebook information must be viewed together to decipher their meaning.

Harvard Plate Stacks Collection

Today, the Harvard Plate Stacks collection holds approximately 600,000 glass plate photographs and thousands of research notebooks and observation logbooks. This comprises the world's largest collection of analog astrophotography and adds 100 years to the current digital record of the Universe. Aside from being the largest, the Harvard Plate Stacks is unique among similar collections in several ways. The photographs were made to create a survey of the sky, and every region of the sky is represented many times over. If a scientist needs to know how a region of the sky looked in 1897 and again in 1922, they are more than likely to find it in the Harvard Plate Stacks. It is the only collection of its kind to be comprehensive in this way.

The collection is also a near-complete record of the evolution of analog photography. Due to the scientific nature and use of the materials, the photographs have been kept in a consistent environment over time, and there is thorough metadata for each plate, including emulsion type and exposure length. This makes the collection an excellent test case for photography conservators [6].

The HPS collection also showcases the rich history of women's work in astronomy. It was using spectra photographs from the

Harvard collection that Cecilia Payne-Gaposchkin discovered the elemental composition of stars, ushering in what we know as "astrophysics" today. It cannot be understated how important these women's research and calculations were in supporting the discoveries of household names like Hubble and Shapley, who built the modern foundation for galactic astronomy.

Analog & Digital Information Management

Cataloging and information management were as important to these pioneering women, who pulled and viewed thousands of analog glass plate negatives at the end of the 19th century, as they are to current astronomers accessing petabytes of images online. Both require key information about the location and equipment used to capture the astronomical images, where the telescope was pointing, and any supporting information written down or entered by the astronomer and researchers. For the astronomical negatives from 18 different types of telescopes at 28 observatories, astronomers and computers recorded this information and important astronomical coordinates on the protective paper jackets that encase the fragile glass plates (Fig. 2). When these plates are digitized, this information must be captured efficiently and accurately for each plate, and permanently linked to the digital images to ensure preservation in a robust and sustainable information management system. A key feature of this process was adding barcodes to the backs of the plate jackets with their plate ID numbers, which are derived from the numbers etched into the glass of each plate when it was initially made. This plate ID serves as its unique identifier.

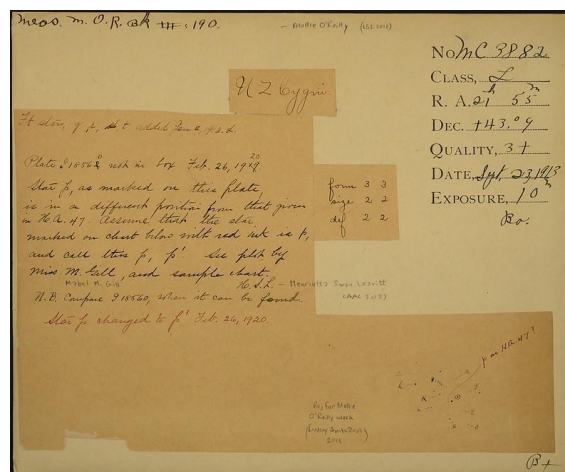


Figure 2. Plate jacket for photograph MC03882 with notes written by Henrietta Swan Leavitt and Mollie O'Reilly.

Digitization of Astronomical Features

Digitizing clear images of the astronomical features while preserving the historical annotations on the plates has been a continued challenge for astronomers, conservators, and curators. Starting in the early 2000s, the first major digitization project, Digital Access to a Sky Century at Harvard (DASCH), scanned 427,000 direct image plates to build a digital dataset for Time-Domain Astronomy. [7]

DASCH opened access to research using the HPS historical dataset to users like never before. It no longer required knowledge and training in reading astronomical information on a glass plate negative. The photometry pipeline for DASCH created a programming solution for much of the analysis previously done by

eye [8]. DASCH's PI, Prof. Josh Grindlay, published the initial results of the first rounds of scans in 2012 [9]. This paper has now been cited over 100 times across astrophysics research. These scientists are examining astrophysical phenomena that are rare or vary on decade-long time scales, including black hole activity, supernovae, and quasars [10]. For example, in 2025, Naoto Kojiguchi et al. discovered a superoutburst using DASCH data [11]. Also, scientists have begun to examine the data through a historical lens. Recently, Louise Breuval and Caroline Huang used DASCH data and Henrietta Swan Leavitt's own archival notebooks as a Women Computer and compared them to modern Gaia space telescope data to analyze Leavitt's research on Cepheid variable stars. She found Leavitt's accuracy to match the limitations of grain in silver gelation of the glass plates [12]. This is compared to Edwin Hubble's work and his Hubble constant, using the same medium and Leavitt's Law, which is off by a factor of 7 [13].

The DASCH digitization scope of work included 427,000 direct-image photographs and plates, in which the light is focused to match what would be seen by the eye. Plates that were out of scope included the ~200,000 spectra plates, plates that were made with prisms or grating, and those that did not include stars (ex., Moon plates, people, instruments). The digital output from DASCH included a Flexible Image Transport System (FITS) file, a non-archival JPG file per glass plate negative, and a JPG file of the negative's paper jacket. The DASCH workflow first photographed the plate using a DSLR camera to produce a JPG. The glass side of the plate was then cleaned of all annotations and finally imaged with the DASCH scanner to obtain the FITS file. FITS is the universal format for scientific astronomical data used by every observatory on Earth and in orbit.[14]

Despite conferences on glass plate digitization [15] and alternative solutions proposed by science historians [16] and photography conservators, the decision to remove the annotations during the cleaning process was a destructive and irreversible solution to obtaining the most unobstructed scientific data possible. The decision not to capture archival-quality image files before removing the annotations has resulted in a poor representation in the Plate Stacks digital and physical record of the research and discoveries made by the Women Astronomical Computers [17].

After imaging, FITS files were processed to produce light curves of star variability and made available on a publicly accessible database [18]. For each plate, the database served JPGs of both the plate and the jacket, and provided access to a cropped region of the full FITS file. A user would enter a query for a specific star and would receive a graph with a light curve plus thumbnails of the FITS files used to generate it. The full FITS file of a plate was not accessible through the public DASCH interface.

Historical and Astronomical Digitization

In 2022, Thom Burns pushed to change course and stop cleaning glass plates before scanning them with DASCH. Thus preserving annotations on approximately 20,000 plates. By 2023, these final plates were scanned, completing the DASCH project. HPS was now able to focus on expanding its digitization and public access goals. They engaged R.B. Toth Associates to develop an improved digitization system. Simultaneously, in collaboration with Peter K.G. Williams, an astrophysicist and data scientist, and software developers, the team produced an expanded database, StarGlass. This publicly available API unifies digitized historical records, metadata, DASCH imagery, and new images produced by multispectral imaging designed for interdisciplinary users across both the sciences and humanities. These images are different from

those produced by DASCH, comprising multiple images in color and grayscale that support the historical and astronomical records.

The multispectral imaging system developed for plates in the HPS Collection (Fig. 3) builds on methodologies and technologies developed over 25 years of narrowband multispectral imaging and analysis experience, employing the latest equipment and techniques.

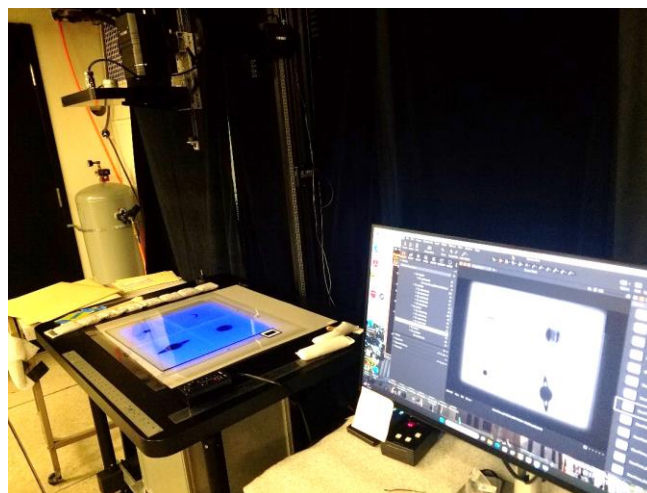


Figure 3. HPS Astronomical glass plates multispectral imaging system.

Multispectral imaging systems are used worldwide in the study of cultural heritage. Universities, museums, and libraries are increasingly incorporating multispectral and other advanced imaging into their digitization workflows to support preservation, access, and research.[19] Working with one of these cultural heritage imaging systems, experimental imaging of glass plates from the collection demonstrated that the photographic emulsion and historic ink markings had different spectral responses. The experimental multispectral imaging produced images of both the astronomical features on the emulsion side of the plates and the historical markings on the glass side (Fig. 4). These images demonstrated that the astronomical features on the emulsion sides of the astronomical plates are clearly visible in all wavelengths of transmitted light illuminating the plates from below. The colored ink historic annotations on the glass sides of the plates, in turn, are clearly visible in shorter wavelengths of light and are transmissive at longer IR wavelengths.

Building on these different spectral responses, the HPS sponsored development of a fully operational narrowband imaging system to digitize thousands of astronomical plates in support of astronomers and researchers.

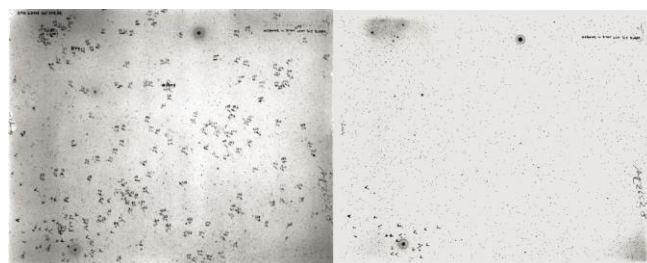


Figure 4. CfA Glass Plate MC26528 emulsion side in green light with visible annotations (left) and in IR light (right)

HPS contractors developed and installed a multispectral imaging system with transmissive illumination in narrow bands of ultraviolet (UV), visible and IR light, building on systems used to image manuscripts, documents, and other cultural heritage artifacts. This enabled the digitization of both astronomical features and historical annotations with the same camera and plate positioning, as well as flexibility for imaging other cultural heritage objects. The HPS multispectral imaging system provides researchers and viewers with digital images that include:

1. High-resolution monochromatic images created from one or multiple bands prioritizing the capturing of the emulsion while minimizing or eliminating the impact of annotations or markings to be used for astronomical data.
2. Historical markings and information on the glass side of the plates, in the context of the astronomical data on the emulsion side, serve as historical information.
3. A reproducible and publishable good resolution color image of each glass plate for publication and viewing as they appear to the human eye, with a consistent background for cultural heritage accuracy, to be used for reproduction and publications.
4. Visualization of deteriorated markings, astronomical objects, and artifacts on the highly variable glass plates, including those with gelatine, tree-based varnish, and water damage.

Astronomical Glass Plates Imaging System

The HPS imaging system is based on experiments and analyses from two test imaging sessions in 2023 and early 2024, along with collaborative requirements meetings in the spring and summer of 2024. Since the historical and astronomical features on the glass plates respond differently in various wavelengths of light, the HPS multispectral imaging system refines the mature technology and system components used in prior narrowband multispectral imaging systems. The system integrates commercial hardware and software for digital multispectral image capture, management, and viewing. It does so by capturing a series of high-quality, registered narrowband digital images with a medium-format 150-megapixel achromatic camera tethered to a computer workstation.

Each image is illuminated by one of 16 specific narrow UV, visible, and IR wavelengths of light from a light-emitting diode (LED) panel under the glass plate on a copy stand with a transparent base plate (Fig. 5). Camera filters are also used to capture faint fluorescence emitted in longer wavelengths from faded ink annotations in additional images. The system incorporates software to operate its lights, camera, and filters efficiently and to produce standardized image data and metadata (Fig. 6).



Figure 5. Narrowband multispectral image capture of an early astronomical photograph of a solar eclipse in 1918, MISC10003

Integrating this system into the HPS digitization workflow allows the HPS to meet multiple goals in providing online access to the astronomical and historic record captured in analog form:

- Prioritizing plates that were out of scope for DASCH, including spectra plates;
- Potential recovery of erased annotations visible under certain wavelengths; and
- Archival quality image files of the plates.



Figure 6. Registered capture multispectral image stack of the total solar eclipse, plate ADH00756

Analog Notes to Digital Metadata/Paradata

A key component of any digitization system is capturing object metadata and permanently linking it to images using structured data models. The object metadata for the astronomical plates includes not just catalog information but also paradata about the collection of photos taken with various telescopes around the globe. In turn, multispectral imaging metadata, paradata and other useful capture information must be collected and preserved to exploit the images fully. This makes a cheap, off-the-shelf barcode scanner one of the most important components of the advanced imaging system. With this scanner, the imager simply scans the barcode on the plate jacket to ingest the plate ID number as the filename without the accuracy and time delays of manual entry. This information is also entered into the TIFF EXIF and an accompanying JSON sidecar file with collection metadata. This immediately links all the resulting images to their respective plates in any database, enabling access to all the associated metadata and paradata from the early astronomers.

Imaging Workflow

Imaging the HPS glass plates requires not just all the necessary hardware and software, but also the development of an efficient workflow for the fragile glass plates, with training and operational support, work processes, and a data pipeline optimized for this application. Plate sizes range from 4x5 inches to 14x17 inches. This requires efficient focusing and focus lock for a series of similar plates, as well as a color target, ruler, and flats/calibration images initially each day and when changing the imaging setup. Key tasks implemented with the system software include:

1. Ingest the glass plate catalog number from the barcode on the plate sleeve captured by the scanner to create the filename.
2. Perform automated capture of a stack of images in up to 16 wavelengths of light.
3. Convert captured images from proprietary format to TIFF and upload to the Harvard University Digital Asset Management System for preservation and access.

4. Produce a color image by combining the achromatic RGB 450 nm (blue), 525 nm (green), and 635 nm (red) visible light images (Fig. 7).
5. Transfer the images to the HPS archival system.

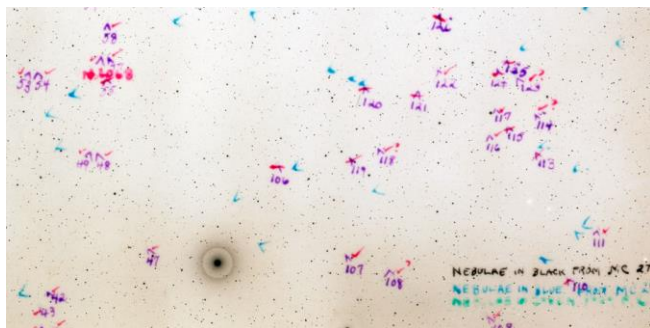


Figure 7. Section color image synthesized from 635 nm (red), 525 nm (green), and 450 nm (blue) light images.

Data Management

Global access to the collected multispectral and scientific data from these systems will help ensure full visibility into the digitization processes and offer more opportunities for objective studies of the empirical data. This requires effective data management to ensure the preservation of the multispectral images and other scientific data from the astronomical plates. [20]

Just as early astronomers photographing the heavens wrote information about the photograph and the astronomical object on the glass plate jackets, now, in the digital age, this and additional digitization information is included with the image data and in the file name. Metadata is entered into a JSON file, including the EXIF header, camera, illumination, and shot settings. The software uses a hierarchical structure for naming each captured image:

project_Plate ID-Digitization Date/Time-wavelength and filter_digital image sequence number_Flattened status.tif

This results in a filename like:

GlassPlates_A21519-2507081313-TX635N_001_R.tif

Which represents the following information:

Harvard Astronomical Glass Plates Plate ID A21519-Digitized 25 July at 08:13:13-635nm transmitted light with no filter_Image 1_Unflattened captured image.tif

This information and the metadata are also stored in a JSON file in a folder with the Object ID and EXIF header. The metadata conforms to basic Dublin Core elements, including object name, rights, publisher, digital object creator, contributors, description, and location. It also includes technical information about the digital capture of the images, such as camera settings and wavelength.

StarGlass and Access to Digital Assets

StarGlass is the front end and Representational State Transfer Application Programming Interface (REST API) for public access to HPS historical images of stars, galaxies, and space [21]. Using a graphic database backend, it brings together plate and jacket images, FITS files from DASCH, the historic research notebooks and telescope logbooks, and all associated metadata. The database features advanced faceted searches, utilizes metadata amassed in curatorial notes, provides an individual astronomer page view that shows a list of an individual's research notebooks and all their mentioned plates, and is adaptable to accept new kinds of data as materials in the collection are cataloged, digitized, and transcribed. The next phase of StarGlass development will build out the infrastructure to provide access to MSI image files via the plate

details page, and future updates will enable cross-institutional collaboration.

Preserving these images requires integrating large datasets into existing databases for astronomical and cultural heritage research. HPS preserves simple data sets in flat files to minimize the potential for obsolescence and data loss due to changing technologies, and to enhance collaboration among researchers and institutions. This requires the efficient capture and management of standardized data for registration and post-processing. All the imaging data and metadata for these manuscripts are hosted on public servers for further review and research. After completion of imaging and conversion, the stacks of converted multispectral TIFF images are uploaded into the HPS enterprise cloud storage system. From there, they will be ingested into StarGlass.

These new image files will be stored with the historic digital files associated with DASCH in StarGlass's Amazon S3 cloud storage. All of StarGlass's data is organized in a NoSQL graph database implemented using Neo4j software running on Amazon Web Services. The future public interface to display the new MSI imagery is still in development but will include both a web browser viewer and the existing API [22]. These new files will supplement existing metadata already available, including ephemeris information about the celestial body with astronomical coordinates in the form of right ascension and declination.

Ongoing Applications

The development of methodologies for digitizing and hosting large datasets of astronomical and multispectral data required development and integration of specialized imaging systems with new technologies and metadata for cross-disciplinary studies. This included a workflow for efficiently collecting, processing, accessing, archiving and collaborating with digital data from other databases. These are contributing to advancements in astronomy, especially the historical record of short-duration events such as supernova and objects with changing luminosity.

These data sets also lend themselves to the development of Artificial Intelligence and machine learning techniques for recognizing and correcting differences in various imaging techniques over the centuries – from early glass plate negatives and refracting telescopes to modern multimirror observatories – and the pioneering women who advanced the field. The suite of computer analysis tools employed by astronomers to efficiently search through large amounts of data may ultimately find application in empowering cultural heritage practitioners and digitizers to enhance and refine their image data and interpret the images more effectively on their own. Further development of a standard toolbox to streamline this enhanced imaging and post-processing may give users greater control over the visualization of complex data sets, supporting further research.

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multispectral imaging system. Peter K.G. Williams, Innovation Scientist at the Center for Astrophysics | Harvard & Smithsonian, was a lead developer of StarGlass and provided expertise on incorporating the new MSI images into StarGlass for use by researchers in the sciences. Harvard Plate Stacks Curatorial Assistants reviewed workflows and provided feedback during beta testing. They were also the digitizers who got the DASCH project across the finish line. This included: Elijah Berk-Silverman, Klaire Chandler, Kevin Jean-Poix, Samantha Joyce, Kayleigh MacDonald, and Meta Partenheimer.

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Thom Burns is the Curator of the Harvard Plate Stacks and a Technical Art Historian with 18 years of museum experience. By utilizing technology to understand the making and meaning of cultural objects, he aims to make collections more meaningful and accessible to a wider audience.

Debora Mayer is the Conservator for Analytical Services and Technical Imaging at the Harvard Weissman Preservation Center. She manages requests from patrons, faculty, students, and staff for analytical services, including specialized imaging and examination of collections. Debora holds a Master of Science from the Winterthur/University of Delaware Program in Art Conservation.

Kayleigh MacDonald is an alt-processing fine art photographer, a digital technician, and a former Curatorial Assistant and HPS multispectral system operator at the Harvard Plate Stacks.