Investigations of Astrolabe Metallurgy Using Synchrotron Radiation

G. Brian Stephenson, Bruce Stephenson, and Dean R. Haeffner

Introduction

The planispheric astrolabe occupies a special place among early scientific instruments because of its mathematical sophistication, its elegant appearance, and its usefulness to astronomers in pre-telescopic times. The operation of the astrolabe is based on the mathematical properties of stereographic projection, concepts that were understood by the time of Ptolemy in the second century A.D.,[1] although surviving instruments are from much later periods. The astrolabe combined a simple instrument for measuring angles (stellar altitudes in particular) with a rotating map of the heavens—in effect, an analog computer that used stereographic projection to preserve angular relationships during its rotation. The key to its success was its compact design, for it combined an observing tool and a calculating device in a portable instrument that an astronomer/astrologer could carry and use to solve many problems. The oldest extant astrolabes are from 9th-century Syria. Astrolabes were made and used in Western Europe until the 17th century. In some Islamic countries, they were used into the 20th century to determine the times of prayer.

Because of their beauty and intricacy, astrolabes are valued as historic artifacts by museums and private collectors. Museum curators want to know the date and place of an astrolabe's making and as much as possible about the maker, in order to understand the manner in which it was made and used, and to appreciate the cultural context in which it existed.[2] These are the same questions asked of other artistic relics from the past. One way in which some of these questions can be answered is by metallurgical analysis of the material (usually brass) from which an astrolabe was fashioned.[3]

Initial Study: Comparison of Two Astrolabes

The Adler Planetarium and Astronomy Museum in Chicago has one of the world's great collections of astrolabes, with more than 70 instruments from the 11th through the 19th centuries, including examples from most of the major regions and of the predominant styles.[4] We wished to explore whether modern synchrotron x-ray techniques offer particular advantages for investigations of the metallurgy of these historical artifacts. To that end, we present here synchrotron x-ray analyses of two astrolabes: M-33a (Adler Planetarium and Astronomy Museum, from the Mensing Collection), and DW0595 (Harvard University, from the David P. Wheatland Collection) (Figure 1).

As shown in Figures 1a and 1b, the two astrolabes are made in a strikingly similar style, and are both signed and dated "Ioannes Bos," and "24 March 1597" (Figures 1c and 1d). Astrolabes were not mass-produced in the 16th century. The identical signatures and dates suggest strongly that there is a problem with at least one of the instruments. These are both, in fact, part of a larger group described in a previous study of potentially fake antique scientific instruments.[5] The Adler instrument, M-33a, differs from the others of that group in being noticeably larger, 125 mm in diameter, while the rest are all about 100 mm. The engraved lines and letters on the Harvard instrument, DW0595, are scribed less precisely, and curatorial inspection yields a strong initial suspicion that M-33a was the original from which DW0595 was copied. The two objects were chosen for study in an attempt to determine whether synchrotron x-ray techniques can quantify such suspicions.

In discussing the instruments, it is helpful to define the nomenclature used for some of the parts:

- The body of an astrolabe, shaped like a hollowed-out disk, is called the *mater.*
- One or more thin, disk-shaped *plates* fit snugly inside the hollow cavity of the mater, fixed so that they will not rotate. Each side of each plate is inscribed with altazimuthal coordinates for a specific latitude. The astrolabe's user must ensure that the plate for the correct latitude is on top of the stack.
- A metal *spacer* fills out the cavity of M-33a, since only one plate remains of the stack that once filled the mater. The spacer is apparently of modern construction.
- The characteristic *rete* (a Latin word for "net") rests atop the plates, held in position by a central pin around which it can rotate. The rete is largely cut away so that the altazimuthal coordinate lines on the plate beneath it are visible. Its intricate shape includes labeled star pointers representing celestial coordinates, typically of a couple of dozen stars. Manual rotation of the rete simulates the apparent daily rotation of the stars around the North Pole.
- A rotating pointer, or *rule,* can be used to line up positions of interest with scales around the rim of the mater.

Approach: Metallurgical Analysis Using Synchrotron Radiation

X-ray techniques provide nondestructive analysis of composition, crystal structure, and thickness with submillimeter spatial resolution. In this work, we used a synchrotron source to produce a highly collimated, small-spot-size beam of high-energy x-rays suitable for such measurements. High-energy x-rays are sufficiently penetrating to allow metal objects several millimeters thick, such as astrolabe components, to be analyzed. High collimation and small spot size allow diffraction patterns to be resolved conveniently using an area detector. The high intensity available allowed us to perform a variety of analyses on each astrolabe component within minutes. Presented in the following are comparisons of the M-33a and DW0595 instruments using fluorescence, diffraction, and radiographic data.

Measurements were carried out at the SRI-CAT beamline 1-BM at the Advanced Photon Source (APS) at Argonne National Laboratory near Chicago.[6] For these ex-

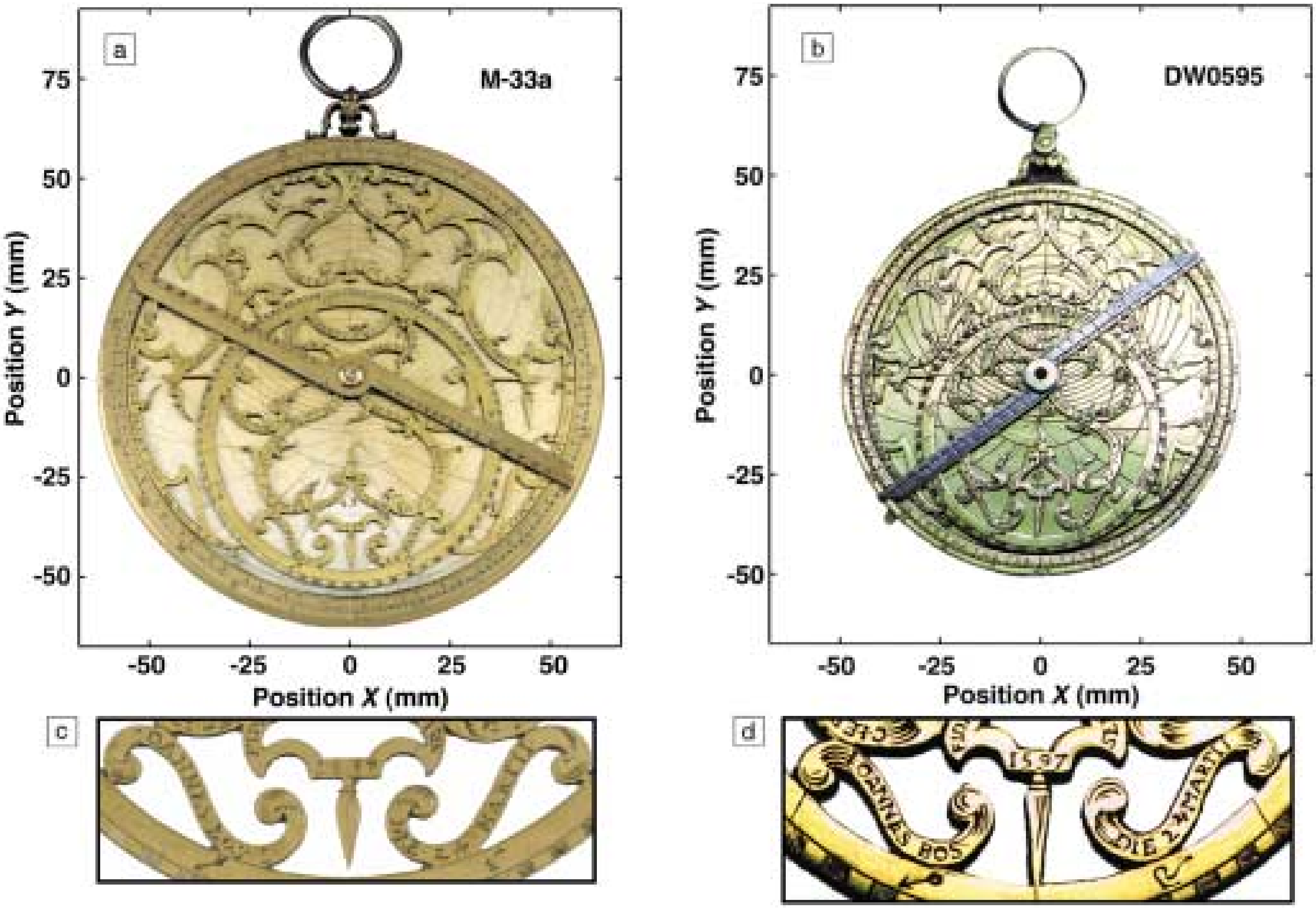

Figure 1. The two astrolabes studied, fully assembled: (a) M-33a (Adler Planetarium and Astronomy Museum, from the Mensing Collection) and (b) DW0595 (Harvard University, from the David P. Wheatland Collection). The axes indicate the (x, y) *millimeter coordinates used to specify locations of analyses. (c), (d) Details of* retes *showing identical style and inscription.*

periments, we set the Si(111) monochromator to 68 keV and used slits to define a beam size of 0.5 mm × 0.5 mm, giving a typical incident intensity of 10^{10} counts/s. The experimental setup is shown in Figure 2. Astrolabe components were secured in nylon grips and mounted on a computer-controlled stage that provided motion with respect to the x-ray beam by remote control. A preliminary study was performed to verify whether exposure of brass to the x-ray beam in air produced any deleterious effects, such as enhanced tarnishing due to ozone formation. No such effects were found, even with prolonged exposure to the 68-keV beam used.

Three types of x-ray analyses were performed, each using a separate detector. For fluorescence analysis, a cooled Ge detector was mounted at 90° to the incident beam, and the sample surface was oriented at 45°, giving a "symmetric reflection" geometry. For diffraction analysis, the sample surface was oriented normal to the incident beam, and an x-ray-sensitive area detector, consisting of a CCD camera coupled to a phosphor, was mounted to monitor diffraction angles of up to 15° surrounding the directly transmitted beam. This transmission diffraction, or "pinhole photograph," geometry is similar to the diffraction geometry of a transmission electron microscope. For scanning radiography, a silicon photodiode in front of the CCD camera intercepted the direct beam transmitted by the sample. To check for spatial variations, fluorescence and diffraction measurements were typically recorded at several locations on each component. The scales shown in Figure 1 indicate the coordinates used to specify locations (millimeters, origin at center).

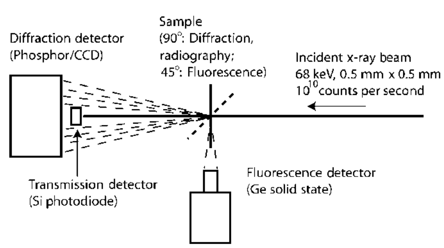

Figure 2. Schematic of the experimental setup, showing arrangement of detectors for fluorescence, diffraction, and radiographic analyses.

Fluorescence Analysis

To determine the elemental composition of artistic or historical artifacts, x-ray fluorescence analysis is preferred[7] to techniques such as emission spectroscopy[8] because it does not require the sacrifice of material from the sample. Historical astrolabes are often made of brass, an alloy composed mainly of copper and zinc. Brasses differ in the Zn/Cu ratio, with more recent brass usually having a higher

Zn content. Brasses used in the manufacture of scientific instruments after the 17th and 18th centuries typically showed higher Zn content than those used previously.[9–11] The concentrations of impurities also give clues to the manufacturing process and place and date of origin. X-ray fluorescence can be used to determine the Zn/Cu ratio and to identify and estimate the concentration of impurity elements with sufficiently high emission energies, that is, atomic numbers higher than about 20 (Ca).

Figure 3 shows typical fluorescence spectra obtained from key components of both the M-33a and DW0595 instruments. Table I gives a semiquantitative comparison of the compositions of these alloys obtained from the peak intensities. Because of the small escape depths of the fluorescent x-rays (also given in Table I), these represent near-surface compositions. The concentrations of several elements (marked with an asterisk) varied with position, and therefore probably represent surface plating.

The M-33a plate is a Cu-15%Zn alloy, with impurities of Ni, Fe, Ag, and Sn (major), and Pb and Sb (minor). Its composition is consistent with that of 16th-century brass made by the calamine cementation process,[11] in which zinc is introduced into copper by heating it with calamine and charcoal. The amount of silver was higher in other locations at which the surface had a silvery color, suggesting an original silver plating that has mostly worn away. It is interesting to compare the composition of the M-33a plate to that of the modern brass spacer within the mater of M-33a. The spacer is a Cu-34%Zn alloy, with minor impurities of Fe, Pb, Cd, Sn, Ag, and Sb. The significantly lower Zn fraction, higher Fe and Sn, and lower Cd concentrations of the M-33a plate relative to the spacer are characteristic of the differences between old and modern brass.[10]

In contrast, fluorescence spectra from the components of DW0595 show no zinc; they are made of copper rather than brass. The spectra show high levels of Au, Hg, Ag, and Pb, which vary with position in a manner consistent with a surface layer of variable thickness. We performed measurements of the density and x-ray absorption of the DW0595 plate, which indicate that the bulk composition is essentially all Cu. The plating on the rete is especially thick, almost obscuring the Cu signal. These components were probably plated with gold using the mercury fire-gilding process,[12] which requires a base of pure or low-alloy copper, rather than brass. Since this process has been known since antiquity, the composition of DW0595 as revealed by x-ray fluorescence does not rule out the authenticity of its 1597 date.

The Adler astrolabe M-33a is unusual for its period in being fastened at the center with a screw and nut instead of the more common axle and cotter pin. Our fluorescence analysis of the screw and nut found that the composition of these parts is similar to that of the plate, corroborating an earlier surmise[4] that they are original.

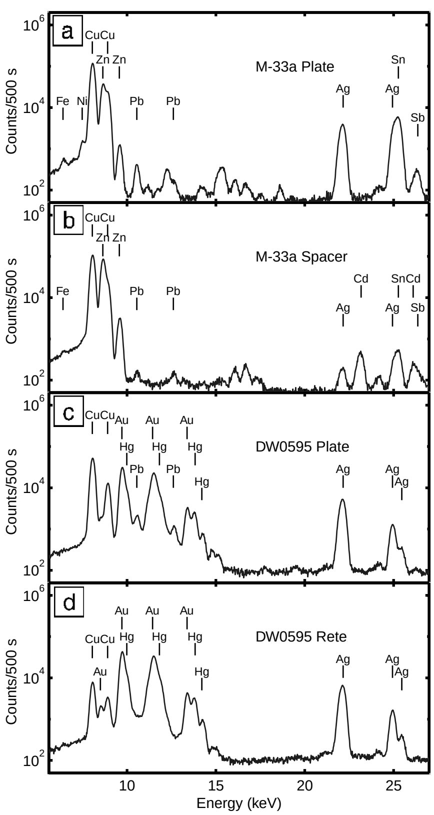

Figure 3. Fluorescence spectra obtained in 500 s from various components at positions indicated: (a) latitude 43 side of plate of M-33a (0, 16); (b) exposed side of spacer of M-33a (0, 5); (c) latitude 43 side of plate of DW0595 (−20, 1); (d) front of rete of DW0595 (0, −30). Each peak is labeled with the element producing it. Note that unlabeled peaks in the energy range of 11–19 keV are detector artifacts (escape and pile-up peaks); observed fluorescence at 24.21 keV is the In K_α background from the detector.

Diffraction Analysis

Transmission x-ray diffraction reveals information about internal material microstructure in a nondestructive manner. The diffraction pattern from a fine-grained polycrystalline metal in which the grains are randomly oriented has the form of concentric rings. Each ring arises from crystalline planes having a specific *d* spacing. Characteristic variations in this ring pattern reveal information about the grain size and texture (preferred orientation) of the polycrystal that gives clues to the processing it has undergone.[13]

- Casting a piece allows larger crystalline grains to form, resulting in fewer, brighter spots scattered around the rings.
- Cold-rolling a sheet produces a certain texture aligned with the direction of rolling, so that the diffraction pattern consists of

Table I: Alloy Compositions Calculated from Fluorescence Data in Figures 3a–3c.

Element	Line	Energy (keV)	M-33a Plate (mole fraction)	M-33a Spacer (mole fraction)	DW0595 Plate (mole fraction)	Escape Depth (mm)
Cu	K_α	8.05	0.83	0.65	0.74*	0.022
Zn	K_α	8.64	0.15	0.34	. . .	0.027
Au	L_α	9.71	. . .	. . .	0.22*	0.005
Hg	L_α	9.99	. . .	. . .	0.03*	0.005
Fe	K_α	6.40	0.005	0.0009	. . .	0.012
Ni	K_α	7.47	0.006	. . .	. . .	0.018
Pb	L_α	10.55	0.0008	0.00018	0.005*	0.006
Ag	K_α	22.16	0.002*	0.00006	0.005*	0.045
Cd	K_α	23.17	. . .	0.00016	. . .	0.051
Sn	K_α	25.27	0.0015	0.00011	. . .	0.065
Sb	K_α	26.36	0.00006	0.00002	. . .	0.074

Note: Calculated mole fractions are semiquantitative, assuming dilute impurities in Cu, taking into account the 68-keV absorption cross sections and escape depths for the various elements and lines, but neglecting all other effects (branching ratios, secondary fluorescence, electron absorption, surface layers, etc.) This analysis gave a measured mole fraction of Au of 0.21 for a Cu_3Au standard, indicating 20% accuracy. Also shown is the escape depth in Cu for each fluorescence line.

*Concentrations varied significantly with measurement location, consistent with a variable-thickness surface plating.

arcs spaced with a particular symmetry, rather than complete rings.

- Recrystallization during heating of such a textured microstructure can change the texture, and thus the symmetry, of the diffraction pattern.
- Manual hammering of a sheet tends to randomize the orientations of the crystals, so that bright arcs appear in all directions around the rings.

Note that unlike fluorescence, transmission diffraction analysis probes the interior of the specimen. It requires a beam of sufficiently high energy to avoid complete absorption in the artifact. The 68-keV beam available at the APS easily penetrates millimeter-thick brass sheets.

Figure 4 shows typical diffraction patterns from four representative astrolabe components. The diffraction pattern from the M-33a plate (Figure 4a) shows rings consisting of random orientations of bright arcs, consistent with thorough working of the plate by manual hammering. The M-33a rete pattern (Figure 4b) is very similar, indicating that the sheet of metal from which the rete was fashioned had also been produced by hammering. Thus, the intricate detail of the rete was likely produced by cutting out many small regions from a sheet, a very laborious process employed in 16th-century astrolabe manufacture.[14] The diffraction pattern from the DW0595 plate (Figure 4c) is strikingly different. The bright spots show a highly directional $\{100\}\langle 001\rangle$ (cube face) texture. We found that the orientation of the texture is identical in different areas of the plate and, in fact, is aligned with the engraving on the plate. This texture is that expected for recrystallized, cold-rolled copper.[13] This would be consistent with the fire-gilding of a modern rolled copper sheet. In addition to the bright spots from the Cu, the diffraction pattern shows weak uniform rings with smaller radii, corresponding to the larger lattice constant of Au, coming from the fine-grained microstructure of the surface gilding. The diffraction pattern from the rete of DW0595 (Figure 4d) shows many randomly oriented bright spots from the Cu, rather than a strong texture. Evidently, the rete of DW0595 was not cut from a rolled sheet similar to that of the plate, but instead it was made by casting.

Scanning Radiography

Hammered metal varies noticeably in thickness across a distance of a centimeter or two, because it is nearly impossible to hammer a sheet to a uniform thickness. A modern rolled metal sheet is highly uniform in thickness. For a sample of uniform composition, the fraction of the x-ray beam that is transmitted gives a measure of the sample thickness. By scanning the sample across a small beam and recording the transmitted intensity at regular intervals (e.g., every 0.5 mm), a thickness profile is obtained along the line that was scanned.

As shown in Figure 5, a typical scan of the x-ray transmission across the M-33a plate reveals irregular thickness variations, consistent with a sheet produced by hammering. A typical scan across the DW0595 plate reveals a uniform thickness characteristic of a rolled sheet. The fine-scale variations probably result from the lines incised in the plate.

The Mystery of Ioannes Bos: The Metal Speaks

Metallurgical analysis using x-rays indicates that the composition and microstructure of the Adler instrument M-33a (apart from the spacer) are consistent with the 1597 date, while those of the Harvard instrument DW0595 indicate a much more recent origin. To say that the metallurgy of M-33a is consistent with the date engraved on it is not the same as confirming that date. We have shown that M-33a was made with technology available 400 years ago: hammered sheets of low-zinc-content brass. On the other hand, DW0595 shows signs of a more modern technology: cold-rolled sheets of copper. Since the process of rolling wide sheets of metal had not been developed by the end of the 16th century,[3] it is unlikely that DW0595 bears an authentic date and signature.

The rete of DW0595 shows crystallography indicating that it was cast. It is plausible that the rete, by far the most intricate component of the instrument, should be made by casting from a mold, since DW0595 is one of a group of identical astrolabes now dispersed among various collections.[5] It appears likely that the instruments in this group are reproductions of M-33a, made at the same time as each other, perhaps as attractive (and extravagant) souvenirs.

Outlook

Of the three measurement types reported, only the diffraction analysis required the intense, highly collimated beam of a synchrotron. A less brilliant laboratory source would have sufficed for the fluorescence analysis and the radiography. The particular advantage of the synchrotron for these two analyses was convenience. Since the artifacts had been removed from museums and taken to the beamline for the diffraction analysis, it was simple and efficient to perform fluorescence analysis and scanning radiography at the same time. The results reported here were obtained nondestructively, in about 36 h of beam time, for 15 astrolabe components and three measurement types. This efficiency is an important consideration for delicate artifacts that must be removed from museum display or storage and transported to the experimental site(s).

Analyses such as those reported here are particularly interesting for comparative purposes. One desires a large number of reference measurements with which to compare a newly measured astrolabe. We intend to continue the types of analysis discussed here with as many of the Adler instruments as possible, to ascertain the composition, microstructure, and thickness profile characteristic of astrolabes from different time periods, geographic regions, and makers. Once these data are collected, statistical analysis will help us evaluate measurements of particular instruments.

More generally, we wish to continue exploring interdisciplinary research opportunities, to see whether the points of view of the physical scientist and the historian can complement one another. In physical science, one studies a sample to learn not about that particular sample but about something more general, a process or a type of material. Variations that are characteristic of a particular object are often of little interest. Historical artifacts, in contrast, are of interest not only as examples of more general classes but often specifically because of their unique attributes.

Study of those very attributes can benefit greatly from the judicious application of analytical methods from the physical sciences. It is only because the techniques of fluorescence analysis, diffraction analysis, and scanning radiography have been developed in a scientific context that they are understood well enough for them to yield understanding of a particular astrolabe signed by Ioannes Bos on 24 March 1597. Yet a focus on a single object can pull us away from generalities into the more complex world that is, in the end, what we are all studying. In simplest terms, the scientist is often interested in reproducible general phenomena, to the neglect of individual variations. The historian may focus on particular details and fail to see beyond them. We think that both scientist and historian can profit from exposure to the other's point of view.

Acknowledgments

The authors wish to thank Martha Goodway for helpful comments, and Armon McPherson and Adam Pyzyna for their help during the experiments. The DW0595 astrolabe was loaned from Harvard University's David P. Wheatland Collection of Historic Scientific Instruments,

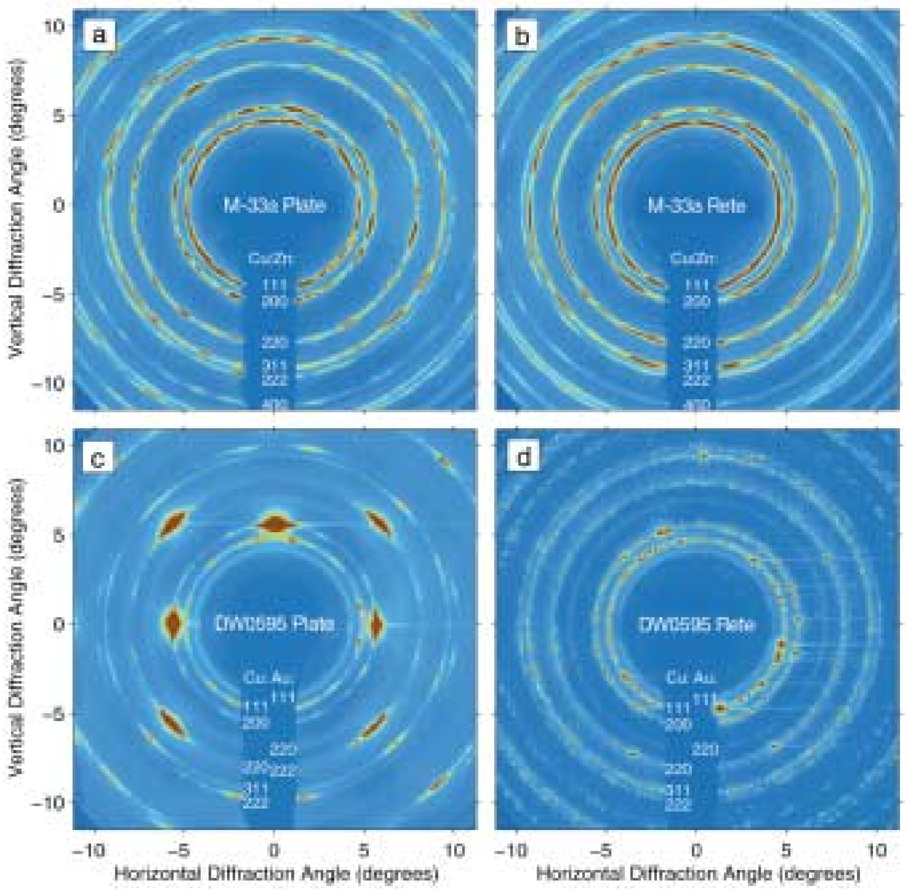

Figure 4. Diffraction patterns obtained in 30 s from various components at positions indicated: (a) plate of M-33a (0, 11); (b) rete of M-33a (0, −51); (c) plate of DW0595 (7, −15); (d) rete of DW0595 (0, −30). Colors toward the red end of the spectrum indicate higher intensities.

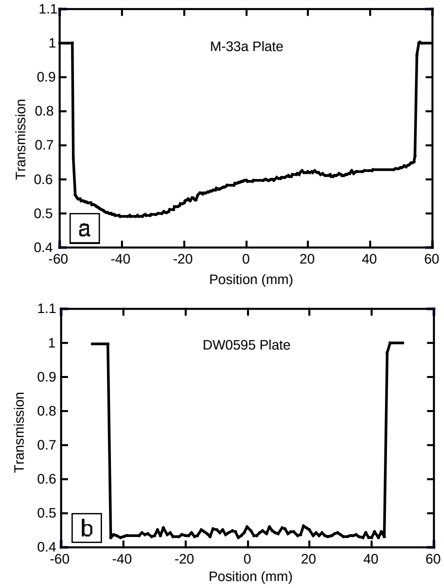

Figure 5. X-ray transmission at 68 keV as a function of distance x across (a) plate of M-33a at y = 3 and (b) plate of DW0595 at y = −3.

Cambridge, Mass., W.F. Andrewes, curator. The M-33a instrument is from the Adler Planetarium and Astronomy Museum, Chicago, Bruce Stephenson, curator. Use of the Advanced Photon Source is supported by the U.S. Department of Energy, BES-DMS, under contract No. W-31-109-ENG-38.

References

1. O. Neugebauer, *Isis* **40** (1949) p. 240; reprinted in *Astronomy and History* (Springer-Verlag, New York, 1983) p. 278.
2. S. Schechner Genuth, in *Western Astrolabes,* edited by R. Webster and M. Webster (Adler Planetarium, Chicago, 1998) p. 2.
3. R.B. Gordon, *Historical Metall.* **20** (1986) p. 93.
4. R. Webster and M. Webster, eds., *Western Astrolabes* (Adler Planetarium, Chicago, 1998).
5. D. Price, in *Actes du VIIIe Congr. Int. d'Histoire des Sciences (1956)* (Gruppo Italiano di Storia delle Scienze, Firenze, 1958), p. 380.
6. J.C. Lang, G. Srajer, J. Wang, and P.L. Lee, *Rev. Sci. Instrum.* **70** (1999) p. 4457.
7. G. Turner, *Interdisciplinary Sci. Rev.* **8** (1983) p. 274.
8. H. Michel, F. Asaro, and A. Norberg, *The Plate of Brass Reexamined: A Supplementary Report,* Appendix 2 (The Bancroft Library, University of California—Berkeley, 1979).
9. C. Mortimer, in *Proc. 25th Int. Symp. on Archaeometry,* edited by Y. Maniatis (Elsevier, 1989) p. 311.
10. D. Hook and P.T. Craddock, Appendix II to J. Day, *Historical Metall.* **22** (1988) p. 38.
11. R.L. Barclay, *Bull. Sci. Instrum. Soc.* **39** (1993) p. 32.
12. P.T. Craddock, *J. Archaeol. Sci.* **4** (1977) p. 103.
13. G.Y. Chin, in *Metals Handbook,* 8th ed., Vol. 8 (American Society for Metals, Metals Park, OH, 1973) p. 229.
14. R.B. Gordon, *Ann. Sci.* **44** (1987) p. 71. □