The composition of bronze mirrors in 18th-century reflecting telescopes

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ABSTRACT: High-tin bronzes were already used for mirrors in antiquity. These alloys were also employed in reflecting telescopes before the availability of silvered glass mirrors of sufficient optical quality. Bronze mirrors from six 18th-century telescopes in the collections of the Musée d'histoire des sciences in Geneva, four of them signed by well-known London instrument makers, were analysed for this study. Their composition is discussed in the context of historic recipes and reference results from other contemporary telescopes.

Introduction

Reflecting telescopes first appeared in the 17th century as an alternative to refractor optics where lens aberrations and the general difficulty of manufacturing quality glass lenses limited the optical performance of larger instruments. Chromatic aberration in particular was considered insurmountable by Isaac Newton who in 1671 presented a reflecting telescope to the Royal Society, using the design which to this day carries his name. His work had been preceded by others, notably by the Scotsman James Gregory from 1663 onwards who used a different design which gained much popularity in the 18th century (Simpson 1992; 2009; Willach 2007). In the 1720s, initial practical difficulties had been overcome and from then on reflecting telescopes were built in significant numbers.

London was internationally the leading city for high quality telescope manufacturing as it combined the scientific knowledge assembled in the Royal Society with manufacturing traditions and important markets for marine and terrestrial use. Numerous specialized family businesses were active as manufacturers of scientific instruments, many of them located in or around Fleet Street. Another Scotsman, James Short (1710–1768), stood out among them for the reputation of his reflector telescopes. By the beginning of the 18th century, earlier experiments with silvered glass mirrors had been abandoned in favour of cast and polished high-tin bronze mirrors.

High-tin bronze, also known as speculum metal, had already been used for hand mirrors in ancient China, ancient Egypt, by the Etruscans and in the Roman Empire. This alloy must be distinguished from tin-plated low-tin bronze which was also used for mirrors in antiquity (Meeks 1993). High-tin bronze fulfilled the conditions of an alloy not too hard to grind into the required paraboloid shape, polishable to a mirror finish, and resistant to tarnish. Judging the accuracy of the mirror shape on historic telescopes remains problematic because of likely later abrasive repolishing to restore the optical performance of the instrument. However,

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the composition of the mirrors has remained unchanged and, together with historic treatises and recipes, gives us an idea of the state of the art of mirror production for telescopes in the 18th century.

Contemporary technical treatises

To reduce spherical aberration, the primary mirror in a telescope had to be given a paraboloid rather than a simple spherical shape, a fact that had already been theoretically understood in the mathematical works of René Descartes in the first half of the 17th century and had become well known to 18th century instrument makers. However, just producing an accurate spherical mirror proved to be difficult enough already, and few 18th century instruments were equipped with true paraboloids. Even the highly respected James Short sold reflectors with simple spherical mirrors alongside others with more or less accurate paraboloids (Willach 2007).

The secondary mirror in a Newtonian reflector (Fig 1) would be flat and therefore be easy to produce, concave (ideally ellipsoidal) in a Gregorian instrument (Fig 2) and convex (ideally hyperboloidal) in a Cassegrain design (Fig 3). Similar to the Gregorian telescope, the Cassegrain configuration had also been presented as a theoretical design in the 17th century but took some time to be mastered practically. On all telescopes examined by Willach (2007), the secondary mirrors were more or less exactly spherical. Unlike the primary mirrors where a paraboloid shape made a significant difference because of their larger diameter, no apparent attempt was made to produce a complex aspherical surface on any of the much smaller secondary mirrors.

In the 18th century, systematic research was carried out to identify the alloy composition best suited for telescope mirrors. Mirror grinding, polishing and testing techniques also improved significantly (Willach 2007; Bennett 2012). The extent of the research into optimising the mirror can be judged from contemporary English and French technical treatises such as Claude Siméon Passemant's detailed instructions how to build a reflecting telescope (Passemant 1738), the equally hands-on instructions by the physician John Mudge (1777) and the clergyman John Edwards (1783), both amateur telescope manufacturers, or the chapter on telescope optics by the French astronomer Jérôme de Lalande quoting John Hadley in his second edition of Jean-Étienne Montucla's earlier *History of Mathematics* (Montucla and de la Lande 1802). The mathematician Robert Smith also quotes research into suitable alloys for the mirrors by instrument makers Samuel Molyneux

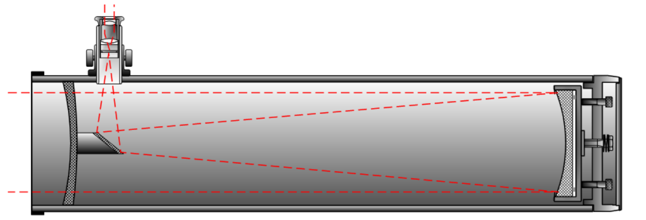

Fig 1: Schematic view of a Newtonian telescope (source: Szőcs Tamás (2009), Makszutov–Newton-távcső.png, licensed under CC BY-SA 2.5, via Wikimedia Commons).

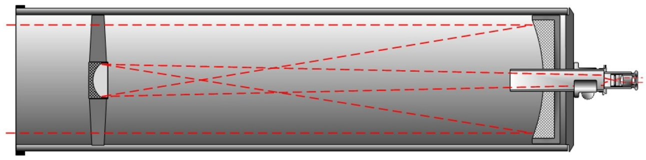

Fig 2: Schematic view of a Gregorian telescope (modified after Szőcs Tamás (2009), Gregory-rendszerű távcső.png, licensed under CC-BY-SA 2.5, via Wikimedia Commons).

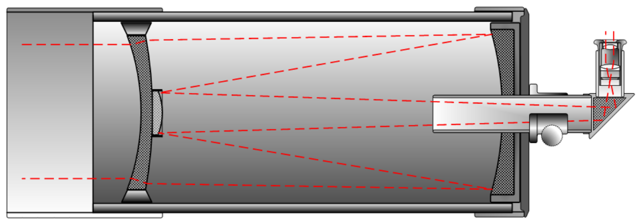

Fig 3: Schematic view of a Cassegrain telescope (source: Szőcs Tamás Tamasflex (2009), Maksutov-Cassegrain.png, licensed under CC BY-SA 3.0, via Wikimedia Commons).

and John Hadley in his comprehensive optics textbook (Smith 1738).

Identifying the best possible alloy was done by trial and error through long series of experiments. The aim was to increase reflectivity to a maximum, for example through the addition of small quantities of silver or arsenic, to limit hardness to what could be ground into the required shape with reasonable effort, and to obtain an alloy as resistant against tarnish as possible.

Table 1 shows a selection of alloys particularly recommended by contemporary authors. The composition of the brass listed as an ingredient in the recipes undoubtedly varied. The percentages in the table were calculated on the basis of a typical 85 Cu/15 Zn brass. The use of recycled brass could have introduced small quantities of other metals, in particular lead. The arsenic featuring in some of the recipes, *arsenic blanc* in French, is arsenic trioxide As_2O_3, not elemental arsenic. As we can see, the recommended tin content in the alloys varied between 25% and 33%. Several recipes point out that increasing the tin content makes the mirror more reflective but also more difficult to prepare because of the particularly high hardness of these alloys.

Table 1: Recipes for the composition of telescope mirrors taken from 18th century texts.

Copper %	Tin %	Zinc %	Arsenic %	Silver %	Comments	Note
71	25	4	–	–	Alloy of John Hadley (1682-1744)	1
57	26	–	17	–	Alloy of Claude-Siméon Passemant (1738)	2
71	29	–	–	–	Alloy recommended by Robert Smith (1738)	3
67	33	–	–	–	Alloy described as very hard by John Mudge (1777)	4
70	30	–	–	–	Preferred alloy of John Mudge (1777)	5
66	30	0.3	1.5	2	Preferred alloy of John Edwards (1783)	6

Notes:

1. '… deux parties de cuivre, une de laiton, et une d'étain suivant Hadley' (Montucla and de la Lande 1802, 501).
2. 'L'on prend vingt onces du plus fin cuivre rouge, qu'on nomme Cuivre-rosette. Neuf onces d'étain d'Angleterre du premier affinage mis en grenailles, au défaut de cet étain on prend de celui qui vient des Indes, qui est par livre, et que l'on nomme Etain en petit chapeau. Huit onces d'arsenic blanc. Telle doit être la proportion des matières qui entrent dans la composition des miroirs.' (Passemant 1738, 25).
3. 'There are various compositions recommended in SMITH's Optics, all which have however their several defects. Three parts copper and one part and one-fourth of tin will make, he says, a very hard white metal; but it is liable to be porous.' (Mudge 1777, 297).
4. 'If the quantity of tin be further increased to a third of the whole composition, it will then have its utmost whiteness; but will be rendered at the same time so exceedingly hard and brittle, that the finest washed emery upon lead or brass will not cut it without breaking up its surface; and the common blue stones used in grinding the speculum, will not touch it. Mr. JACKSON (some time since dead) a mathematical-instrument-maker, and a most excellent workman, told me, that the tin was increased to the above proportion in his metals …' (Mudge 1777, 297–298).
5. 'I at last found that fourteen ounces and an half of grain-tin to two pounds of good Swedish copper, made a beautiful white and very hard metal …' (Mudge 1777, 298).
6. '[Alloy No] 47: Copper 32, Tin 15, Brass 1, Silver 1, Arsenic 1 - a most excellent Metal, being by much the whitest, hardest, and the most reflective I have ever yet met with.' (Edwards 1783, 27). Edwards conducted systematic experiments with numerous additional alloying elements added to the high-tin bronze (silver, platinum, iron, lead, antimony, arsenic, bismuth and zinc) in order to find the optimum alloy for his mirrors. He also offers practical advice how to mix, melt and cast the metal.

Willach (2007) published the only other analytical study of the composition of historic telescope mirrors known to the authors. He had a total of 22 historic telescope mirrors analyzed, all of them from the 18th century. Eleven of these originated from the famous workshop of James Short in London. The analyses confirmed the use of a relatively uniform alloy consisting of 25–29% tin, <0.6% zinc, 0.2–2% lead and 0.1–0.6% arsenic, the remainder being copper.

Today these alloys come under the name of high-tin bronze (Scott 1991; Meeks 1993). Above *c*19% tin, bronzes take on a silver colour which is due to the δ phase with the stoichiometric formula $Cu_{31}Sn_8$ becoming dominant. Up to 32.5% tin which is the nominal composition of the pure δ phase, metastable below 350°C (Fig 4), high tin bronzes are binary alloys. Between approximately 19 and 27% tin we have a saturated solid solution of tin in copper (α phase) and α+δ eutectoid. Between 27% tin (the composition of the eutectoid) and 32.5%, it is a mixture of the eutectoid and δ phases. The particularly hard high-tin bronzes containing 32–34% tin consist of almost pure δ phase with a very high Vickers microhardness of 390–440 (Srinivasan and Glover 1998). In practice, the tin content of speculum metal does not exceed 33–34% because this would introduce the ε phase (Cu_3Sn) into the alloy which has a Vickers hardness similar to the δ phase (Ghosh 2004), making the grinding of the mirror impractical. Also, the ε phase tends to give a bluish colour to the alloy (Murase *et al* 2011).

Certain characteristics of the δ phase (hard and deformation resistant, silver colour, highly polishable with good corrosion resistance) were very attractive for manufacturing mirrors. The presence of a small quantity of α phase (yellow, less hard and of inferior corrosion resistance) in the eutectoid for a tin content below 32.5% was a necessary compromise to enable the mirror to be shaped by abrasion. It was the accuracy of the final shape of the mirror where the outstanding telescope manufacturers distinguished themselves and for which trade secrets were jealously kept (Simpson 2009).

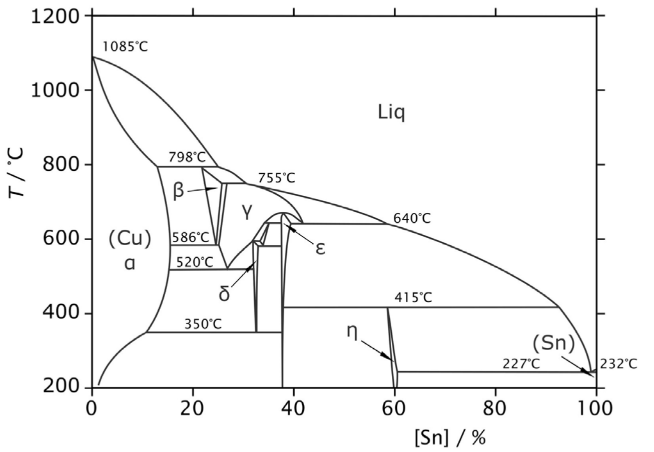

Fig 4: Cu-Sn equilibrium phase diagram (modified after Metallos (2007), Cu-Sn-phase-diagram-greek.svg, licensed under CC BY-SA 3.0, via Wikimedia Commons).

Telescopes investigated for this study

For this study, the composition of six primary telescope mirrors instruments in the collection of the Musée d'histoire des sciences (MHS) in Geneva were analysed. The secondary mirrors could not be examined because they were too complex to dismount from inside the barrel. Four of the instruments carry makers' inscriptions from the mid-/late 18th century, the other two are likely to be contemporary or just slightly later.

Gregorian telescope, inv. MHS 25

This small demonstration telescope (Fig 5) is held by a simple wooden table stand and has a 345mm (13.6") long barrel, a 52mm (2") primary mirror and an incomplete eyepiece. It does not carry a maker's inscription and dates presumably from the end of the 18th century.

Gregorian telescope made by George Adams, inv. MHS 115

This telescope on a folding brass claw tripod (Fig 6a) has a 645mm (25.4") long barrel, a 99mm (3.9") diameter primary mirror and a Huygens eyepiece. The eyepiece carries the inscription 'G Adams N°60 / Fleet Street London' in two lines (Fig 6b). It allows the instrument to be dated between 1766 when houses in Fleet Street started to be numbered and 1795 when George Adams junior died (Millburn 2000). Its design is very similar to the telescope inv. PH.329778 in the North American Museum of American History (https://americanhistory.si.edu/collections/search/object/nmah_1184344) which carries an identical inscription. The Geneva telescope is slightly longer than its counterpart from the Smithsonian Institute.

Fig 5: Telescope inv. MHS 25, probably late 18th century (photo: MHS).

Fig 6a: Telescope inv. MHS 115, made by George Adams, London between 1766 and 1795 (photo: MHS).

Fig 6b: Telescope inv. MHS 115, maker's inscription (photo: authors).

Newtonian telescope made by George Adams, inv. MHS 116

The telescope, also mounted on a folding brass claw tripod (Fig 7a), has a 620mm (24.4") long barrel, an 84mm (3.3") diameter primary mirror and a Galilean eyepiece with a single biconcave lens. The unusual Galilean eyepiece may not be original as the instrument does not produce an image. A Newtonian telescope would normally have a convex eyepiece lens. The inscription on the barrel 'Made by GEO ·ADAMS in Fleet-street, London. F' (Fig 7b) indicates a date between 1734 when George Adams senior set up his workshop at Fleet Street and 1795 when George Adams junior died. From 1766 houses in Fleet Street were numbered (Millburn 2000, see above). The absence of a house number in the inscription suggests a date between 1734 and 1766.

Gregorian telescope made by James Short, inv. MHS 1665

This demonstration telescope, mounted on its wooden storage box (Fig 8a), carries the signature 'James Short London 221/898 = 9.4.' engraved on its back plate behind the primary mirror (Fig 8b). This allows the instrument to be dated between 1738, the year of his moving from Edinburgh to London, and 1768 when he died (Turner 1969). The barrel of the instrument measures 340mm (13.4") and carries a 63.5mm (2.5") diameter primary mirror. The serial number indicates that this is the 221st instrument of type 9 in James Short's sales catalogue, and No 898 of all instruments he built (Turner 1969). This information should undoubtedly allow the year when the instrument was made to be determined more precisely. The telescope includes two eyepieces of the Huygens type.

Fig 7a: Telescope inv. MHS 116, made by George Adams, London, between 1734 and 1766 (photo: MHS).

Fig 7b: Telescope inv. MHS 116, maker's inscription (photo: MHS).

Fig 8a: Telescope inv. MHS 1665, made by James Short, London, between 1738 and 1768 (photo: MHS).

Fig 8b: Telescope inv. MHS 1665, maker's inscription (photo: authors).

Gregorian telescope made by Edward Nairne & Thomas Blunt, inv. MHS 2547

This telescope on a folding brass claw tripod (Fig 9a) has a 660mm (26'') long barrel, a 100mm (3.9'') diameter primary mirror, a Huygens eyepiece and a second incomplete eyepiece. The dimensions of the instrument are almost identical to inv. MHS 115 by George Adams. The makers' inscription 'Nairne & Blunt London 3/130 = 2/587' features on the barrel (Fig 9b). The serial number 587, instrument number 130 of Nairne & Blunt's model 3, allows the telescope to be dated just after Edward Nairne's association with Thomas Blunt in 1774. Another reflector carrying the serial No 573, sold at auction in London on 27 March 1972 (Turner 1979), was still signed by Nairne alone. In any case our instrument dates before July 1793 when the partnership between the two craftsmen came to an end (Turner 1979).

Gregorian telescope, inv. MHS 2787

This small demonstration telescope (Fig 10) with a barrel merely 213mm (8.4'') long, a 45mm (1.8'') diameter primary mirror and a Huygens eyepiece does not carry a maker's inscription. A handwritten note in 19th- or early 20th-century German *Kurrent* script suggests that the instrument should be used in school to explain the design of a Gregorian reflector. The age of the telescope is somewhat uncertain, it could be a 19th-century instrument.

Fig 9a: Telescope inv. MHS 2547, made by Edward Nairne and Thomas Blunt, London, c1776 (photo: MHS).

Fig 9b: Telescope inv. MHS 2547, makers' inscription (photo: MHS).

X-ray fluorescence analysis

The primary mirrors were removed from the telescopes and analysed with a Thermo Niton XL3t 950 Goldd+ portable X-ray fluorescence (XRF) spectrometer with Ag anode and 3mm spot size, mounted on a portable box stand by EMSE Elektromechanik Swen Eberstein, Wolfratshausen, Germany. For quantification, the factory calibrated 'Mining' mode was used, measuring at 3, 8, 20, and 50kV for a total of 120s per analysis.

Detection limits were <0.1% for all elements. For As in the presence of >1% Pb (which was not found in our alloys) the detection limit would have been c. 1% because of the interference of the Pb Lα with the As Kα line. 'Not detected' (nd) in Table 2 indicates that there was no element peak above background level in the spectra.

Two areas were analysed on each mirror, one on the polished face, the other on the back of the mirror. On two of the mirrors (MHS 115 and 2547), both readings were taken on the polished face because the back was too corroded to give a valid quantitative result. Table 2 shows the results of the analyses.

Discussion

The compositions of five of the six high-tin bronze mirrors, including the four signed instruments from London, form a homogenous group with 25–29% tin, traces of lead and arsenic but no other alloying elements.

Fig 10: Telescope inv. MHS 2787, probably late 18th or 19th century (photo: MHS).

Table 2: Alloy composition of the primary mirrors (nd = not detected).

%	MHS 25		MHS 115		MHS 116		MHS 1665		MHS 2547		MHS 2787	
	Face	Back	Face 1	Face 2	Face	Back	Face	Back	Face 1	Face 2	Face	Back
Copper	73	73	71	71	74	71	74	72	75	74	75	75
Tin	25	25	29	29	26	25	26	27	25	25	21	21
Zinc	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Lead	0.3	0.3	nd	nd	0.1	0.1	0.1	nd	nd	nd	0.3	0.3
Arsenic	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.5	0.5	0.3	0.3
Antimony	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	1.3	1.4
Bismuth	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	1.3	1.1
Silver	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

It is identical to the alloys used elsewhere by James Short and other contemporary London manufacturers (Willach 2007). The tin content in our mirrors remains below the 30–33% favoured by John Mudge and John Edwards following their comprehensive systematic testing of alloys in the 1770s (Table 1). There is no evidence that in actual practice these very hard alloys were ever used to a significant extent because none of the 22 telescope mirrors analysed by Willach (2007) presented a tin content above 29%. We can assume that the practical difficulties of grinding such a very hard alloy outweighed any slight benefits in reflectivity and corrosion resistance that there may have been. In any case the uniformity of the analytical results demonstrates that the alloy composition of the mirrors was carefully controlled.

The small demonstration telescope MHS 2787 sets itself apart with less tin at 21% and the presence of antimony and bismuth at per cent levels. Despite its lower tin content, this alloy has still got a silver colour but would be less corrosion resistant and significantly easier to grind, confirming the status of the telescope as a modest teaching instrument.

It is worth noting the absence of arsenic, silver and zinc at per cent level, elements which feature in some but not all of the historic recipes. The traces of < 0.5% lead and arsenic present in our mirrors should not be considered deliberate additions to the alloys. Zinc appears only to be present in the early telescope mirrors from the beginning of the 18th century. It features in the recipe attributed to John Hadley (1682–1744) (Table 1) who in 1721 launched the first successful production of refractors other than the experimental forerunners by Newton, Cock and Hooke of the 1670s, some of which used silvered glass mirrors (Willach 2007; Simpson 2009). The absence of zinc in our mirrors confirms the historical dating of our instruments to the mid or late 18th century.

Conclusion

The analysis of six 18th-century reflector telescope mirrors from the collections of the Musée d'histoire des sciences in Geneva has demonstrated the close similarity of the alloys, high-tin bronzes with 25–29% tin and traces of lead and arsenic. One small teaching instrument of unknown provenance uses a different alloy, inferior but easier to shape, with just 21% tin. These alloys match various contemporary recipes as well as results from other 18th century reflectors, notably those by the highly recognized London manufacturer James Short.

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