Reconstructing the *Auloi* from Queen Amanishakheto’s Pyramid

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**Zusammenfassung**


“The condition of various parts of the Meroë auloi is such that a complete restoration, even of a single instrument, is not possible. This is, of course, a great loss since there still remain several technical questions which, if settled in a positive way, would eliminate many moot points with respect to Graeco-Egyptian music of the period near the birth of Christ.”

1 Bodley 1946, 218.

2 Dunham 1957, 109 pl. LIX A, B.

**2 The Problem**

The tomb of Queen Amanishakheto was excavated in 1921 by the *Harvard University – Museum of Fine Arts Expedition* to the sites of the Meroitic kingdom. When a cache of several pipes was found embedded in the filling of the stairway leading to the burial chamber, these were correctly identified as belonging to the class of doublepipes well known from Mediterranean archaeology, which we normally designate by their Greek name, *aulós* (plural *auloi*). Two photographs were taken of the instruments *in situ*, but these show only the location of a few pieces, with the rest still buried beneath. The find was extracted and placed in a number of boxes in which the pieces remained until recently, stored at the Museum of Fine Arts (MFA), Boston, although also repeatedly handled by known and unknown scholars and museum staff over the course of almost a century.

Twenty-five years after their excavation, the items were described by Nicholas Bodley, who ar-
rived at the utterly pessimistic conclusion quoted above. Not having succeeded in joining a complete pipe or even a longer section of a pipe, Bodley based his views about the musical scales the instruments might have played on the ideas of Kathleen Schlesinger, who believed that fingerhole distances would have been constant along an aulos. Schlesinger’s assumptions, however, have long been discredited on firm archaeological and philological grounds, and with a little more effort, Bodley would have realised that fingerhole distances varied considerably on the Meroë instruments, too.

Indeed, Bodley’s material may incite despair. For many years I had experienced this with the most complex fragment he describes, consisting of the end of a bone bulb joined to a piece of tube with two fingerholes, one of which is connected to a side-tube that leans in the direction away from the bulb (Fig. 1). As is well known, a bulb always belongs to the mouthpiece end of an aulos, while a side-tube has the physical effect of lowering the pitch of a fingerhole. With the direction of the pipe defined by the presence of the bulb, the two fingerholes would thus represent the index and thumb holes. The pitch of the index fingerhole, however, is lowered by the side-tube in a way that we must expect it to coincide almost exactly with that of the thumb hole. Therefore it seems that the ancient aulos makers would have gone to considerable technical length to produce an instrument that makes no sense. At this point I had given up in despair, time and again.

In 2015, however, the MFA generously offered me the opportunity to investigate the fragments myself, together with Susanne Gänsicke, then Conservator of Objects at the MFA, Peter Holmes, specialist on music-related ancient metalwork, and Olga Sutkowska, who had already seen and catalogued the items (Fig. 2). Since the summer of 2013, Susanne Gänsicke had led a special conservation project focused on the preservation of the instruments that had originally been connected. In one instance, we joined two parts of a bone bulb – in a perfect fit – one of which was still perfectly white, while the other was uniformly stained by green copper corrosion products. Obviously the two parts had been separated already in the ground, perhaps even during burial. On the other hand, many of the metal cylinders that make up the instruments’ many sections still preserve their smooth rims, while the interior tubing of bone or wood which held them together was lost or deteriorated at the ends, thus preventing the search for physical joints.

On a more positive note, the same day dissolved my great conundrum, giving way to new hope for musically understanding the items. On closer inspection, the problematic assemblage of bulb end, tube and side-tube turned out to be a chimera. The side-tube clearly did not belong on the fingerhole where Bodley either found it or put it; neither was there any basis for associating the loosely fitting bone socket with that particular metal tube. To my great relief, reason and common sense were thus restored to the ancient aulos makers.

Fortunately nowadays we are in a much better position than Bodley found himself in more than seventy years ago. Not only have many more finds of auloi been published; more importantly, the scales of some of them have been analysed and found to be in excellent agreement with the pitches and scales known from ancient theory, ancient notation and the remains of ancient notated music.

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3 Bodley 1946. Recently the instruments were featured in Kuronen 2004, 61.
5 In fact Bodley indicates hypothetical interhole distances for different sorts of pipes without specifying the fragments to which these would apply or the method by which he arrived at such figures, given that he does not propose any joints; furthermore it becomes clear that his respective work was not based on measurements of the fragments themselves, but of photographs, and this without taking photographic distortion into account (cf. Hagel 2012a).
6 This is acknowledged by Byrne (2000, 281), who however does not realise that without a hole further up the tube it cannot be “necessary to duplicate a hole on both sides of the instrument for use by thumb or II”.
7 This project was funded by generous donations from members of the Visiting Committees of the Departments of Musical Instruments, Art of the Ancient World, and Conservation and Collections Management, and continued until 2016. Since July 2016, Gänsicke has worked as Senior Conservator of Antiquities at the J. Paul Getty Museum, Los Angeles.
We have also learned more about the ways the different notes worked together harmonically in different periods, with a major shift from the 'flat' to the 'sharp' keys between the Hellenistic and Roman Imperial periods.\(^{12}\) Notably, the Meroë instruments were deposited right in the middle of the period in which this shift occurred, a period from which, as I have said above, written melodies are tantalisingly absent. Finally, the art of experimental aulos playing has also started to thrive in recent years, with expert craftsmen such as Robin Howell and professional pipers such as Barnaby Brown and Callum Armstrong devoting their ingenuity and their experience with extant traditions to reconstructions of ancient instruments; furthermore, I have shown that it is possible to work the known ancient types of woodwind mechanism not only between pieces, as has often been assumed, but during playing.

These two kinds of mechanism, which have been described long ago,\(^ {11}\) are both found on the Meroë instruments. The probably older type consists of a sliding plate connected to a rod with a knob on its upper end. By pushing that knob down towards the end of the pipe using (mostly) the small finger, a hole can be closed that is beyond the reach of the hand, and opened again by pulling the protruding knob upwards, towards the mouth end. The other kind of mechanism is considerably more sophisticated regarding its production. It requires the bone core of the pipe to be covered by a perfect cylinder of metal, around which other cylinders revolve, each of which is equipped with a knob that can be operated by any finger. By pushing these knobs from the side of the instrument to the upper side and pulling them back again, individual fingerholes are covered and uncovered. Sometimes a single outer cylinder extends over more than one fingerhole; this may either serve as a switch between two holes, or open and close several at once, or a mixture of both. The ancient mechanisms, it will be noticed, differ from modern woodwind mechanisms on a very basic level: not incorporating any springs, they do not revert to a default state when released. Instead of giving momentary access to various notes, they put the instrument into a different configuration, affecting either the mode or the playing range or the available bass note.

The Meroë find includes many rotating 'sleeves', but only four sliders. The latter are most exquisitely produced, the cover plate being worked in the shape of a shell in the mouth of a dolphin (Fig. 3). The sleeves are also technically more advanced than any other finds I have seen, but this is not the place to discuss details of engineering.

Facing about 110 cylindrical sections of various pipes, eleven bulbs and numerous remains of reed inserts, not to mention uncountable bits of bone and metal, I had to acknowledge that no established methodology would lead anywhere. Reconstruction, if possible at all, would have to be based on a number of working hypotheses, proceeding in a hermeneutic spiral that would reinforce some of them while others would have to be dismissed, ultimately hoping for results whose internal stringency would substantiate the initial assumptions so convincingly that no one could call the whole edifice a petitio principii.

3 Methods

So from which hypotheses did we set out? Firstly, we assumed, on the basis of all known aulos finds, that the internal bore of each pipe would be cylindrical. Sections with different internal diameters would therefore belong to different pipes. Consequently we were able to separate those whose bore could be measured into at least three distinct classes. The same holds true for outer diameters: existing instruments are all cylindrical at the outside as well, apart from the bulb plus reed-insert cone at the upper end and possibly a small bell on the lower. This assigned many fragments with a missing or highly damaged bone core to one or the other of the classes that had been established from the bore diameters. Thirdly, some of the metal tubes held remnants of wooden cores. Accordingly, it seemed reasonable to classify the fragments into bone-core and wood-core pipes, tentatively assigning to the latter those tubes which display no remnants of glued bone on their insides at all.

All this would still not assemble the parts. For this, I needed structural assumptions. Firstly, any assumed configuration would need to be physically playable. The human hand, even if highly trained, cannot finger any combination of five holes (at the upper end where the thumb hole of an aulos sits below the index finger hole) or four holes (further down the pipes). For any hypothetical reconstruction I therefore needed to assess its physical plausibility. During the sessions at the MFA this was done with the help of a wooden rod of suitable diameter, on which I marked the assumed hole positions in order to check whether my hands would be able to span them. Having been trained on the considerable distances required for the lower regions of the Louvre and Pompeii pipes as well as for my reconstructed 'spondeion aulos', I could hope not to fall too short of an ancient professional aulète's physique.

\(^{10}\) Hagel 2009b, 49–50, 361–364.

\(^{11}\) For rotating sleeves cf. Howard 1893; for sliders, Conze 1903, 7–8; Byrne 2002; For a general overview, Sutkowska 2015.
Secondly, the notes would need to make some musical sense. This applies to several possible levels. On a very basic one, the beauty of aulos music depended on a harmonious interplay between the two pipes — notwithstanding the use of dissonances to create tension — and so we expect to detect, and have so far detected on all well-studied instruments, the ancient consonances of fifths, fourths and (if the ambitus is large enough) octaves. On another level, we know the ancient theorists’ accounts of scales in terms of their melodic intervals, coming in diatonic, chromatic and enharmonic flavours. In recent years, progress was also made in relating the abstract systems of theory to instrumental reality. Therefore I would look for valid ancient scales, even though these come in a great variety. Apart from those described by Aristoxenus and his followers (and rendered numerically by other writers according to the ‘Pythagorean’ paradigm), the reconstructed older ‘pipe scale’ consisting of tones and couples of approximate three-quarter-tone intervals must be taken into account. We know at least from the ‘Berlin aulos’ as compared to the ‘Louvre aulos’ that ancient doublepipes may have exhibited a well-defined relative scale that was not tied to a particular pitch. Other instruments, especially modulating ones with rotating sleeves, were built to a pitch standard that seems to have stayed quite stable over centuries: here each note in the system of ancient notation was associated with a (more or less?) fixed pitch, as would also have been required by the famous pitched resonators which Vitruvius attests for Greek stone theatres. On the highest level, we must therefore look for fingerholes playing the particular pitches of individual notes, forming scales that fit within the ancient system of notation.

Secondary characteristics may also prove relevant. From the Pompeii auloi, for instance, it is known that larger holes are associated with structurally more prominent notes, which also appear more often in the extant melodies, and in harmonically more prominent functions. On the same instruments, two different types of knobs are found — commonly the knobs are ring-shaped, but on a particular modulating sleeve, a globular knob was mounted.

An attempt at restoring the instruments can only be based on a combination of all these features and considerations, taking into account not a single fixed state of ancient music, but its historical development, as far as it can be grasped from the sources, including the possible co-existence of diverse stages of this development. Much of this only requires an intimate familiarity with the various musical sources and their interpretation. However, what I needed most was a means of relating arrangements of the Meroë fragments directly to approximate ancient pitches.

Fortunately, the physics of cylindrical woodwind playing in the lowest register (as auloi were normally played) is straightforward enough: for fingerholes of the same size and a given distance, the interval between the pitches depends on their distance from a theoretical effective reed end whose location can be treated as a constant throughout the pipe. For small fingerholes one would have to take into account the distance to the adjacent lower open fingerholes, but aulos fingerholes are typically so large that this can be neglected in a first approximation. Since the pitches of the individual ancient notes are roughly known, each of these notes translates into a distance from the effective reed end (which is close to but not identical with the tip of a material reed). So it is possible to print a grid of these distances, providing, for instance, for the full series of semitones of ancient notation, as created by the circle of fifths through which the Aristoxenian keys proceed. When I created such a grid on the first evening of our first stay, Peter Holmes wisely advised me not to design it for a single pitch standard, but to allow for a certain range, printing slightly converging lines for the notes instead of parallels. This enabled me to experiment with various hypotheses, making my life far more complicated for a while. But the additional effort paid off in the end. I was not able to make sense of any instrument except on the basis of the single pitch standard that I had planned to adopt solely — the one which I had previously obtained from the Pompeii pipes and other data. This fact alone, were there no concurrent evidence, would demonstrate that the results are not a mere construction: why would a construction that is not related to ancient reality work out only for the attested chamber pitch?

With the grid, which measured about one and a half metres, laid out on the desk, I proceeded from the fragments with more than one fingerhole: these would need to fit in a meaningful place, where the fingerholes were aligned with the lines (producing tones and/or semitones), or perhaps also with one hole falling in between two lines when two others are aligned with lines a minor third apart (giving the more archaic pipe design). For fingerholes larger or smaller than the others in the row, one would have to infer a slight pitch shift upwards or downwards, respectively. The side-tubes, of which the find contains three, are also unproblematic, as they effectively shift the position of their hole (i.e. the hole in the pipe without the side-tube attached) downwards by roughly the amount of their height.
In this way, the very few fragments with more than two holes easily find one or perhaps two plausible positions. Those with two closely spaced holes would assign themselves to a semitone step in the higher region of the gamut, while two more widely spaced holes might span either a semitone in the lower region, or a tone in the higher – or be situated in between wherever the three-quarter-tone option needed to be taken into account. Starting from such nuclei I tried fitting smaller fragments in both directions, so that their holes would continue a meaningful scale. The cylindrical fragments would of course not give their direction away, so it was necessary to try all of them in both ways. Wherever there is a rotating sleeve with a knob or at least solder traces where a knob had once been attached, there is at least a clear association between the assigned direction and its belonging either to a left-hand or a right-hand pipe, as the knobs do always point towards the playing hand. They usually stand at a bit more than a right angle sideways from an open hole, towards the left on a left-hand pipe, towards the right on a right-hand pipe. However, where there is only one hole on a fragment, this might always be a pipe’s thumbhole as well, in which case the relation would be reversed. And whenever there are two holes on opposite sides, one of them would be a thumbhole, but one would not a priori know which one. In all these cases, four different options must be considered, inverting the fragments both as regards their direction in the pipe and as regards their upside and downside.

After many days of trial and error, it was nevertheless possible to arrive at a stage where all fragments of one type or another would have found their places, forming either complete instruments or instruments where only small parts were destroyed beyond recovery. Instruments can, of course, be regarded as complete only when not only do the pipes yield a meaningful scale, but two pipes complement each other harmonically. In the end, I was always forced to work with all fragments of one type at once, and even needed to consider transferring from one pool to another some sections whose diameters were not securely established.15

4 Knob Shape as a Musical Marker

In one instance, I experienced how far expectations that are formed from experience with other finds may mislead. Guided by the Pompeii instruments, I assumed that the single rotating ring with a globular knob would belong to a ‘modulating’ note alien to the typical mode or modes of its pipe. Admittedly I was a bit troubled by the fact that the associated fingerhole was particularly large, which one would not have expected for a modally secondary note. But then, there had to be a reason for the divergent knob shape. At the end of our first ten-day session I had to give up on the heavily modulating and rather high-pitched pipes to which that section obviously belonged. The more even spacing that a high-pitched series of semitones enforces, in order to accommodate the breadth of the fingers,16 encumbered their interpretation, and we were running out of time. Another day, I thought, would have revealed the correct solution, as it had done for the other sets of pipes. When I returned to the same fragments a few months later, however, three full days would not get me any closer to the truth. In the end I was able to establish an important physical joint, which finally brought the breakthrough – together with giving up the idea of a modulating knob. It now seems that its unique shape indeed had a precise musical meaning, albeit contrary to what I had expected. In fact it appears to mark the central point of the ancient scalar system, the note known as the Lydian mésé, notated as I < (a).17 This would now explain the large size of the fingerhole as well, which would have optimised the tone quality for the most important note – the note from which, according to ancient sources, all other notes in the scale were felt to derive their function.18

But this was not the only working hypothesis that I had to renounce, only the most frustrating one. The others were in fact quite helpful crutches, without which I would not easily have got to the point where they could eventually be left behind.

5 Core Material

At the start of our work, I devoted my attention to the fragments with the largest diameters, to which the four dolphin sliders also belong, and which incorporated some of the longest pieces of tubing, with traces of a wooden core. After a while it turned out that these were the remnants of two pairs of pipes that shared many important musical characteristics. All four sliders, it emerged, were situated within the same region, perhaps even at the same pitch (Fig. 4), the two extant rods being of identical length (Fig. 5). The pitch of the hole which they operated on must therefore have been paramount for the music of these instruments. Also, all the ex-

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15 If the labels we had assigned to the fragments stayed attached to them during this chaotic process, the credit for this belongs to Olga Sutkowska who followed my jumbling around with fully warranted suspicion.
17 For the centrality of this note cf. Winnington-Ingram 1936, 3–9; Hagel 2009b, 117–122.
18 Cf. e.g. ps.-Aristotelian Problems 19.22; 19.36; Cleonides 11, p.202.3–5 Jan; Dio Chrysostom 68.7.
tant holes in the highest region, those covered by the player’s fingers, were identical in position – not between all four pipes, of course, but between the respective higher and lower members of each pair (Fig. 6). This discovery was the key to a relatively fast restoration of the most relevant features of these instruments, because it was now possible to assess sizes and, partially, structures of damaged and destroyed parts on the basis of the analogous member of the other pair. Since destruction had occurred on different places of the tubes, the pairs would in this way complement each other to a certain degree. This led to a partial reconstruction that included a bit less material than what is shown in Figure 7. While this stage already revealed the extraordinary length of the instruments, amounting to almost a metre, as well as their exciting tonality, both unprecedented in the archaeological record, the large gaps in the reconstruction appeared problematic. Given the obviously careful retrieval of even small metal fragments by the excavators, how could the disappearance of so much tubing be explained? After all, two entire end sections seemed to be missing, while the other two had partially survived, partially been puzzled together to almost their full length by Susanne Gänsicke.

Another mystery was posed by two pieces of bone-core pipe with very widely spaced finger-holes, all equipped with rotating sleeves. Olga Sutkowska had played a central role in putting these together on the basis of the excavation photographs and physical joints (Fig. 8). Their internal diameter was larger than in the other fragments, but the spacing of holes would only fit the bass region on a very long pipe. Were they adjustable drones, of which only the ends in bone and metal survived, which had originally been mounted on a wooden cylinder without metal encasing? Such a bare wooden pipe would indeed have left hardly any trace – the preserved fragments of wood survived only thanks to being shielded by surrounding metal tubes, both mechanically and by being imbued with copper corrosion products. Once the possibility of a combination of wooden and bone cores within one and the same pipe had to be admitted, a much better solution offered itself. The two pieces provided the missing ends of the two long pipes that lacked ‘bell’ sections. Not only did they complement the lengths of those pipes down to about the bottom note of the other pair; their holes also seemed to make musical sense. It became clear that in spite of their general similarities the two pairs of long pipes were of quite different sophistication. One of them could only switch between two bass notes by means of the slider: one from the slider hole itself, one from the end of the pipe. The other pair, in contrast, gave access to intervening notes as well, so that the lowest notes could vary between performances.

Once the barrier between wood and bone had broken down, a set of additional unassigned fragments with sleeves begged to be integrated within the same instruments. In this way, we had now four virtually complete pipes (Fig. 9). The small gaps that still remain seemed likely located at points where the instruments had been broken in antiquity before they were deposited. Where there was no bone substructure whose construction in sections helped to contain the damage within a narrow area and later supported the encasing, the bent and cracked metal around crushed and splintered wood, soon decaying, naturally disintegrated into the innumerable very small fragments which defy reconstruction.

6 Bore Shape

The reconstruction of these large pipes also exploded another assumption. Instead of having an entirely cylindrical bore, the width of the bore in the bass section appears wider than that above the centre of the instrument. The details cannot be worked out because the profile of the wooden tubes is lost, which made up a large part of the instruments. Most probably, the adoption of a slightly flaring design was motivated by the need for a better sound of the bass notes, and probably facilitated their production as well. Apart from musical considerations, such a design would also have allowed the makers to exploit animal bones that were too large for other uses. Cylindrical bone of the right size, only a few usable centimetres of which one could obtain from one animal, was without doubt a valuable resource, as also transpires from the fact that in these instruments wood seems to have been used wherever feasible.

7 Bulbs

This is also true for the third type of pipes in the cache. These were shorter, with only very few rotating sleeves mounted over bone cores; everywhere else the tubes consisted of bronze-covered wood. But these instruments held another surprise. From the existence of eleven bone bulbs, some with a decorative silver ring, we had originally expected to find eleven pipes, or perhaps twelve, allowing for the complete disintegration of one bulb. Real-
ity was again more complex. The bronze tubes assigned to the present type of pipes, most of them set apart from the rest also by a certain kind of corrosion, contained more flaring ends than there might have been pipes, given the overall length of tubing as well as the number of fingerholes and especially thumb holes. Although the sections had mostly fallen apart neatly at their boundaries, I found that some of them could be physically joined on the basis of very typical corrosion patterns, caused by being buried next to other pipes that left dark lines where metal lay next to metal, or, at other places, green or white marks. Such a joint evidently placed what had seemed a bell above instead of below the section with the fingerholes (whose direction could easily be identified by the placement of the thumbhole, second from top). Some of those ‘bells’, it thus turned out, were instead reed inserts – a fact that would probably have been obvious if we still had the wooden cores. In this way all the flaring ends found their place and a previously unknown shape of aulos emerged. Or, not entirely unknown, since the find from Poetovio, studied by Olga Sutkowska, who generously shared her data with me, has also no bulbs, but flaring upper ends (as is required for a reed insert). However, since this design was so unusual, one might have considered the possibility of wooden bulbs that had disappeared. Now the Poetovio pipes and the Meroë find safely confirm each other: not all ancient doublepipes of Greek, Italic or Greco-Roman make were equipped with a slanting side-tube, which is identifiable from the Pompeii pipes. The calculations for all existing substantial fragments of all three instrument types have found their homes, it must be cautioned that details may still be subject to change; however, this will most probably affect only the ends of the instruments, and therefore only their bass notes.

In the selected pair, the right-hand pipe is equipped with a slanting side-tube, which is identifiable in make, though not in size, to the other two, which however belong on the long instruments. This may imply that these two sets, being very different in all other respects, nevertheless came from the same workshop.

As described above, my method of reconstruction already involved the definition of an effective reed tip, in relation to which the fingerhole distances were laid out. Taking careful measurements of the relative positions is not all too complicated a task in our example, since there are no gaps: at least parts of each rim of every section survive. This is however only true for the distances between the holes (and from each hole to the ends of the pipe), which are crucial for the pitches the instrument plays. It is more difficult to retrieve their lateral disposition, i.e. to assess whether a certain fingerhole might be shifted clockwise or counterclockwise to another, and by which angle. This task mostly depends on a painstaking evaluation of corrosion patterns, in order to establish how exactly two adjacent sections had been joined while still in the ground. As this is not always possible, it is fortunate that the evaluation of the scales is not at all affected by the azimuths of the various fingerholes; but when it comes to building a playable model or replica, the original disposition becomes a crucial factor, as it greatly influences the ways a pipe can be held and played.

When the scales and intervals for the various fingerholes are calculated, it emerges that good effective reed lengths measure between 2.4 cm and 3.7 cm, on the basis of the current reconstruction. In this way, little more than the reed blades would have extended from the insert. This is possible, but since the parts between the highest fingerhole and the top end consist of indiscriminate tubing, where the joints can only be assessed on the slippery basis of corrosion patterns, it is still possible that these parts may turn out to have been shorter. Figure 11 represents a compromise between optimised intervals and approximation to the pitch standard of other finds, with effective reed lengths of (currently) 2.4 cm and 2.8 cm, and a theoretical pitch standard less than a tenth of a tone below that of the Pompeii pipes. The calculations for all fingerholes ought to be quite exact for the measured parameters, with some uncertainty pertaining to the second-lowest fingerhole of the higher pipe.

8 Meroë WS 3 & 4: An Almost Complete Instrument

This is not the place to develop and discuss the musical implications of the entire set of instruments. But the description of the process in which so numerous fragments were arranged to what might hopefully be their original order (or mostly so) would be incomplete without giving at least one example of what we may learn from it, and also how it is complemented and completed by computer-modelling and experimental reconstruction.

For this purpose I have selected one of the simpler pairs, belonging to the class with mostly wooden cores, only a few rotating sleeves and no bulbs. Such a choice seems reasonable, on the one hand, because the tonality of this instrument is more easily explained within the context of our current knowledge; on the other, because thanks to its straightforward design it was among the first we embarked on making playable models of. Figure 10 shows the fragments laid out in the sequence of the present reconstruction, with the reed inserts to the right and the exit ends to the left. As long as not all existing substantial fragments of all three instrument types have found their homes, it must be cautioned that details may still be subject to change; however, this will most probably affect only the ends of the instruments, and therefore only their bass notes.

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which is equipped with the side-tube (showing as 198.9 Hz). The actual pitches of the bass notes, with all fingerholes closed, will probably have been higher. The metal encasing ends in a small bell, which the internal bore almost certainly followed, slightly raising the pitch as compared to a cylindrical continuation down to the exit. Since the wooden core has perished, however, there was no way of determining the original curvature, and the given frequencies were calculated for a cylindrical bore. From the rest of the design it appears that the bell would have raised the bass notes by about 25–40 cents, creating a good octave and eleventh from the lowest pitch of the lower pipe to the respective notes of the higher. However, here we must also bear in mind that the bass note sections can be finally ascertained only within the framework of a theory incorporating all the material of all twelve pipes.

The treble note of the pair is Lydian nêth diezeugménôn Θ^IN, identical with the highest note on the cithara and the highest fingerhole on Pompeii Pipes 2 & 3, as well as that on the lower pipe of the Louvre aulos.22 The lowest fingerholes, as far as we can see, played CC, which is hyπâtē, originally the lowest note on the lyre, and also the lowest note of the Louvre instrument. On the longer pipe, the bass note with all fingerholes closed appears to be Lydian hyπâtē hyπatôn ΠΓ, also found as the bass note of Pompeii Pipe 76892 and well attested in the musical fragments, too, as a typical lowest note, plausibly associated with the aulos.21 The interval between these two notes is an eleventh; otherwise an eleventh between bass and treble note is not only found on the instrument from Pompeii, but also on the Louvre and the Berlin auloī. The frequent choice of this ambitus is doubtless related to the fact that a cylindrical reed pipe overblows to the twelfth. Overblowing the bass note thus sounds a pitch a whole tone above the non-overblown treble note, in this way extending the scale upwards without either a gap or an overlap. The bass note of the shorter pipe, finally, appears to be one semitone higher than that of the longer pipe. Such an arrangement is known from the Berlin aulos: overblowing it gives again the next note in the scale.22 The lower part of the instruments, at any rate, is not equipped with fingerholes, so that the semitone between the two bass notes is not part of a scale that can be used melodically. As the higher of the two is hardly a useful drone note either, the design (if reconstructed correctly) almost certainly indicates that the instrument was intended for overblowing these two notes.

However, despite the general similarity, the Meroë pair also differs substantially from the Berlin aulos design. On the former, just as on the Louvre aulos, the lowest note is the proslambanô-emos, structural A (using the note letters in the sense of relative pitches in a diatonic scale). On our instrument, it is a tone higher, B. Consequently the overblown notes are not e’ and f’ above a highest fingerhole giving d’, as on the Berlin aulos, but f’ sharp and g’ above a highest fingerhole e’. In other words, the overblown notes would belong to the neighbouring key and would be notated as OK and Eι. This key would be Hypolydian; however, the Hypolydian double octave does not extend beyond Θ^IN, so that the overblown notes actually fall outside the scheme of keys. But we have also examples of notated music that extends beyond the scheme of tônoi, both below and above,23 and the Hypolydian scale notated in the koinē hormasia also rises an entire octave above the theoretical limit, including the two notes in question here.24

The region of the fingerholes, below which there are larger intervals to the exit of the pipes, therefore spans the ‘central octave’, identical with the ambitus of the seven-stringed lyre.25 The key is Lydian, the ancient natural key, but including the first modulating flat and sharp notes. The flat note, ÔV (in Figure 11 labelled as Iastian or enharmonic H> of similar pitch), properly belongs to the neighbouring keys of Hyperlydian/Hypophrygian (which are functionally equivalent, but separated by an octave). Most ancient theorists would however have described it in a different way, as belonging to the Lydian synêménôn tetrachord, I < ÔV ΓΝ ΣΓ, which accounted for the most typical modulation towards the flat keys without conceiving it as an actual modulation – much in the way many Medieval theorists accepted the existence of a b durum and a b molle side by side. The additional sharp note is OK; apart from modulating into the Hypolydian, it is also used in the chromatic variant of the Lydian as the khrômatikê (or, more technically, likhanós khrômatikê mesôn). This note is of the highest importance for the art of the cithara; the second century CE still knows it under the name of khrômatikê, even though Ptolemy’s account of cithara tunings never sports an actual chromatic tetrachord at this point.26 Both these ‘modulating’ notes are present on the lower

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22 For various playing configurations on such an instrument cf. Hagel 2010, 79–81.
25 See below for the possible inclusion of an additional note (hyπerpyatē) that would extend the ambitus to that of the cithara with nine or more strings.
Reconstructing the Auloi from Queen Amanishakheto’s Pyramid

Pipe only; in contrast, the higher pipe includes the regular Lydian parypáte $P$ a semitone below $OK$, and does not divide the tone between mésé $L$ and paramésé $Z$. From Figure 13, the lower pipe incorporates the hand span that combines the most frequently used ancient notes in the best possible way, from $ZC$ down to $CC$.

In the following, I will facilitate the orientation of those readers who are not perfectly familiar with ancient notation by transcribing the ancient notes to modern note names, assigning the natural key to Lydian. It must be borne in mind that the resulting modern notes differ in pitch from those found on a modern instrument by almost a tone. The specific chamber pitch of our reconstructed instrument is around 486 Hz, which is 172 cents higher than our $a = 440$ Hz. That said, the ambitus of the pair extends, without overblowing, from $B$ up to $e’$. The available notes, without half-stopping or specially manipulating the reed are thus the following:

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Hand</th>
<th>Vocal Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS4</td>
<td>right</td>
<td>$?$ C O M I $\ominus$ Z</td>
</tr>
<tr>
<td>WS3</td>
<td>left</td>
<td>$?$ C P I $Z E U \ominus$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Hand</th>
<th>Instrumental Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS4</td>
<td>right</td>
<td>$?$ C K $\ominus$ I $&lt; VE$</td>
</tr>
<tr>
<td>WS3</td>
<td>left</td>
<td>$?$ C $&lt; C U I \eta$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Hand</th>
<th>Functional Transcription ($a \approx 486$ Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS4</td>
<td>right</td>
<td>$B?$ e f♯ g $a^{(\dagger)}$ b♭ b</td>
</tr>
<tr>
<td>WS3</td>
<td>left</td>
<td>C? e f a b c d e’</td>
</tr>
</tbody>
</table>

On each pipe, a pair of adjacent fingerholes are equipped with rotating sleeves; these are greyed in the table. In addition the third hole from the top of WS4 was elongated upwards to a kind of teardrop shape, apparently in order to facilitate half-stopping it (Fig. 14). When the small upper part was released, the pitch would rise by a small amount. This amount was certainly smaller than a semitone (as the next higher hole played), and can therefore only be identified with an enharmonic diēsis, the smallest interval of ancient music, which Aristoxenus as well as harmonicists before him had defined as a quartetone. The present instrument thus provides the first published material evidence for the enharmonic genus, according to Aristoxenus the hallmark of “the Greek, the beautiful music”.

Is it by accident that the quartetone teardrop occurs not in one of the predominant scales of the instrument, Lydian or Hypolydian, but in the modulating tetrachord, which properly belongs to Hypophrygian? The sources are contradictory as regards the association of modes and genera. On the one hand, Dorian is found linked to the enharmonic, in contrast to a predilection of the Phrygian for the diatonic. On the other, Aristoxenus thinks that the ‘division of the semitone’ occurred first in Phrygian and Lydian music. Actually it may not have been technically feasible to incorporate a similar teardrop hole in the Lydian/Hypolydian tetrachord ($ZC-\ThetaH, b-e’$). The hole in question is there furnished with a rotating sleeve, and it sits so close to the upper edge of that sleeve that there was no space for elongating it to teardrop shape. Playing an enharmonic quartetone at this point of the scale thus required half-stopping the next higher fingerhole. As this hole belongs to the middle finger, half-stopping it is easily achieved by sliding that finger upwards. For the quartetone on

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27 Cf. also Byrne 2000, 280.
28 For the ancient discourse around the size of the enharmonic diēsis cf. Hagel 2009b, 413–429.
29 Aristoxenus ap. [Plutarch], De musica 1135c.
31 Aristoxenus in [Plutarch], De musica 1135b, cf. also 1143B on a particular piece of archaic music in enharmonic Phrygian.
the other pipe a similar action would have involved the thumb, which supports the instrument against its weight and the pressure of the other fingers and is therefore less equipped to perform the required fine rolling motion. On balance, it seems safe to conclude that the teardrop hole in its particular position is sufficiently motivated by technical considerations, and we need not search for a specific musical reason for not having it elsewhere as well.

The disposition of the few rotating sleeves can tell us more about the possible harmonic functions of the available notes. On the lower pipe, one could select between having either $M$ (g) and $O$ ($\flat$) in combination with both $C$ (e) and, probably, $\Gamma$ (B) below, or both $M$ (g) and $O$ ($\sharp$) but without the bass note (by the way, the $C$ fingerhole needs to sit at the left side of the instrument, otherwise it cannot be reached by the small finger). In other words, a Hypolydian scale is available only without the bass note of the instrument, even if this note may have formed a fifth with the single specific Hypolydian note, $O$. On the other hand, whenever either $M$ (g) or $O$ ($\flat$) are closed, there is always a gap in the scale unless it is complemented by $P$ (f) from the other pipe. If we include this note, switching between $M$ (g) and $O$ ($\sharp$) results in tetrachords that differ in genus. What one obtains is either simple diatonic $C$–$P$–$M$–$I (< e–f–g–a), or alternatively $C$–$P$–$\Pi$–$\Omega$–$\Lambda$ (< e–f–$\flat$–a), which is a chromatic tetrachord ($\Pi$ being equivalent in pitch with $O$, as far as the standard chromatic shape is concerned). This means that whenever the bass note is kept available, the sleeves of the lower pipe do not switch between keys, but between diatonic and chromatic — in ancient terminology, a modulation of genus, not of tónos. Since, as we have said, the bass note of $\Gamma$ appears to be of particular importance for aulos music, it seems likely that this modulation of genus was more important, while the Hypolydian scale may only have been a secondary alternative. With the enharmonic option emerging from the teardrop-shaped hole, the aulos was apparently designed to play in all three genera.

Turning to the mechanism on the higher pipe, there one may have both $Z$ (b) and $E$ (c) with $P$ (f) as the lowest note, or close one of the former in order to be able to stop $P$ (f) and go down to the crucial hypáte $C$ (e). Stopping $P$ (f) is made possible by the upwards-leaning side-tube; but even with its help it is almost a superhuman endeavour, and it took me weeks to train my hand to handling the enormous span even for a brief period (my left hand, being used to the lowest playing position of Pompeii Pipe 2, had acquired at least 2 cm more span; but here it is the right hand that is strained more). The optional notes are both part of the diatonic scale, so their selection may have been a question of harmonic detail rather than a basic decision about the type of scale. However, while a diatonic, and with half-stopping $U$ (d) a chromatic, highest tetrachord were available with only the hole for $E$ (c) open, since $Z$ (b) could be supplied from the other pipes, an enharmonic tetrachord required both optional holes. Playing enharmonic at this part of the scale therefore precluded a playing mode where $C$ (e) is accessible on each pipe. Unless, that is, one plugs the sidetube. Indeed we ought to reckon with plugs in addition to the rotating sleeves: while the latter are located within the fingered region and may thus be operated during performance, holes below the reach of the hand might have been stopped with plugs instead — a less costly and similarly efficient way, which needs to be posited for the Louvre and the Berlin auloi, too.

Notably, the lowest hole on the higher pipe has no sleeve and cannot be reached by any finger either. And yet there is a substantial length of tube below it, which seems not to be there for purely aesthetic reasons. If that were the case, we would rather expect two pipes of equal length, not one that is slightly shorter. But, as we have seen in the preceding, producing the note a semitone above the bass note of the other pipe would make excellent musical sense. Consequently we would expect that the bass note was used also on the lower pipe, and this requires plugging its $C$ (e) hole.

If the use of plugs, made of wood or bone or wax, is granted, we may wonder whether there was an additional hole on the lower pipe as well. A substantial part of the tube is missing from this section, starting in the region where a hole would come to lie that gives $\Phi$ (d), which is not only the lowest note, called hypátpete, of the contemporary cithara, but also a harmonically important note in many ancient melodies. The damage that incurred at this place would be quite typical (see Fig. 15): while the long cylinder towards the bell remained more stable, the short bridge of material between the hole and the upper end of the section would easily yield to pressure and break in; subsequently, the damage would spread further down the section. Unfortunately we cannot expect that this question will eventually be solved with the help of the remaining minute metal fragments. Though Susanne Gänsicke is still making progress on this front, most of what can be done in this respect has probably been achieved.

I conclude my argument with a reference to one of the most vexing problems of ancient Greek musical studies, pertaining to enharmonic melodies. In one of the musical handbooks for the Roman period, ascribed to a certain Bacchius and probably dating from the first half of the second century CE, two me-

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lodic figures are mentioned: eklysis, a falling three-quarter tone motion, and ekkolé, a rise of five quarter tones. Both are defined not to occur between notes internal to the tetrachord, and only in the enharmonic. Later Bacchius gives notated examples for each of the two terms. That for eklysis, however, does not accord with his definitions, since it involves two inner notes. On top of this, it can be made to work only if the first of the two notes, EΛ, is understood in its enharmonic flavour (b°), while the other, ÏV, must be read as diatonic/chromatic (b'). But the signs do not convey this distinction – it is a mystery how a modulation between chromatic and enharmonic might have been notated at all. Many years ago I speculated about emending the text of the example in a way that does justice to the definitions, assuming that EΛ was wrongly duplicated from the example for the ekkolé, and replacing it with ΖΓ (b°). I do not know if this is the correct solution, though I still cannot see another way of establishing coherence. At any rate, the lower pipe of our instrument appears perfectly designed for playing my proposed form of eklysis. The figure is most easily executed by first lifting both index and middle finger (while the thumb remains on its hole, supporting the instrument), and then putting the index down. In this way the melody moves from the highest note of the pipe, paramése ΖΓ (b°), three quartertones down to the enharmonic diesis created by the tear-drop extension, enharmonic trité synéménon ÏV (a°). Subsequently the melody may return to the harmonic centre of mése I < (a) by placing the middle finger over the tip of the teardrop. Possibly it was this traditional melodic feature, perceived as archaic by the ancient writers, but still found important enough to be mentioned by several sources from the Roman period, that motivated the invention of such teardrop-shaped holes, or at least the inclusion of one at this particular place. The falling nature of the interval is important: since it would be difficult to anticipate the proper amount of half-stopping a hole when approaching a quartertone from above, it is of the greatest help to have it included in the instrument design. The ekkolé can be performed on the higher pipe, exactly in the way indicated by Bacchius; but the case of this rising interval is naturally very different. Here the quartertone EΛ (b°) is the starting point, with the middle finger half-covering its hole, from which releasing the thumb hole brings about the ekkolé up to UΛ (d). Before, the quartertone note may have been arrived at from the note below by pulling the finger away. In contrast to a falling motion, the musician here maintains full control over the pitch, the pitch shift itself being perceptible, so that it can be subjected to the incredibly fast adjustment loop that the human brain is able to transfer from its native purpose for voice production to the control of instruments.

This brief example must suffice to indicate how a reconstructed instrument needs to be evaluated in the wider context of ancient music. Whenever such an evaluation sheds new light on ill-understood details and long-standing questions, or provides a material background for ancient theorems, this will in turn add credibility to the reconstruction. Of course, no interpretation can be considered complete until it is tested in practice. The advance of technology in recent years has greatly facilitated this task. Instead of spending hours on the lathe or searching for suitable plastic tubes, thanks to the accessibility of 3D printing I have transferred a great part of the process of building working models to the desk and the computer. This saves time – working time, that is, since one may have to wait for the product – but it also eliminates sources of error: large mistakes in transferring data from paper to the material object, but also less consequential small-scale imprecision. With a suitably designed interface, it is only a small step from the database of measurements to a programmatic 3D model, with all the fingerholes in place, a proper reed insert, and an exact bore. For the side tube, Peter Holmes had kindly prepared a series of photographs that enabled me to create a model photogrammetrically, which I then combined with the tube. Printed in a suitable material – not too bendable and not too brittle – and equipped with proper aulos reeds of the right size, the resulting pipes allow testing the predicted musical characteristics as well as the feasibility of finger spans and hand positions. All this has been done for the discussed instruments, with the generous support of Middlesex University through Peter Holmes and Neil Melton. Where necessary, various configurations of plugs can be used instead of the original rotating sleeves.

Printing the latter is not strictly impossible (though it may require manual adjustment), but with the available materials the resulting thin layers of plastic were too vulnerable to provide really playable instruments. A true reconstruction in metal and bone (or artificial bone/ivory) is therefore still indispensable for a full assessment of the

33 Bacchius 36–37; cf. Aristides Quintilianus 1.11, p. 28.1–7 Winnington-Ingram; [Plutarch], _De musica_ 1141b.
34 Bacchius 41–42.
35 This is the solution of Zanoncelli 1990, 294. Meibom changes the target note to H>, maintaining the pitch, but notating it in enharmonic fashion – but this still gives an interval between two tetrachord-internal notes.
36 For the ‘chromatic strokes’ that the tables of Alypius have in the Lydian cf. Hagel 2009b, 51–52.
37 Hagel 2000, 59–70.
38 On this instrument, Meibom’s and Zanoncelli’s _éklysis_ would require switching the melody from one pipe to the other.
musical potential of such instruments; I hope that we will at some point be able (and funded) to produce instruments that resemble the originals in all their musical and visual glory.

9 Acknowledgements

This study would not have been possible without the generous funding and support of the Museum of Fine Arts, Boston. Apart from Susanne Gänsicke, whose pivotal role in the project has become clear in the text, I wish to thank Damon Beale, Lawrence Berman, Michele Derrick, Denise Doxey, Rita Freed, Pamela Hatchfield, Christine Kondoleon, Jayme Kurland, Darcy Kuronen, Gwen Manthey, Meredith Montague, Richard Newman, Matthew Siegal and Joel Thompson.

My dear friends Olga Sutkowska and Peter Holmes not only provided invaluable support for my tonality-centred endeavours while carrying out their own studies of the material, but also a heart-warming atmosphere of seamless teamwork as well as the necessary supply of onion rings.
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Fig. 1 Aggregate of bulb socket, tube section and side tube (Bodley 1946, 230 cf. Plate V.9).

Fig. 2 Working on the Meroë instruments in May 2015 (from left to right: Susanne Gänsicke, MFA; Peter Holmes, Middlesex University; Stefan Hagel, Austrian Academy of Sciences; Olga Sutkowska, Berlin University of the Arts). Photograph: MFA, Boston.

Fig. 3 Shell-shaped slider plate held by a dolphin, from the Meroë Long Pipes. Photograph: MFA, Boston.
Fig. 4 Sliders and rough slider hole positions on the Meroë Long Pipes. Photograph: Stefan Hagel.

Fig. 5 Matching slider rod lengths on the Meroë Long Pipes. Photograph: Stefan Hagel.
Fig. 6 Matching fingerhole, side tube and section boundary positions on the Meroë Long Pipes. Photograph: Stefan Hagel.

Fig. 7 The Meroë Long Pipes after the first evaluation. Photograph: Stefan Hagel.

Fig. 8 One of the excavation photographs, and part of a pipe assembled from it (and a bit further). Idea and photograph: Susanne Gänsicke.
Fig. 9  The Meroë Long Pipes at the stage of writing. Photograph: Stefan Hagel.

Fig. 10  The Short 'Wood' Pipes 3 & 4 at the stage of writing. Photographs: Stefan Hagel.

Fig. 11  Physically modelling the scales of Meroë WS 3 & 4. Software and screenshot: Stefan Hagel.
Fig. 12 The notes of Meroë WS 3 & 4 within the context of the fifteen-scales system of ancient notation, indicating the approximate tonal regions of extant Hellenistic and Roman-Imperial musical documents (for the diagram of notes cf. Hagel 2009b, 48 dia. 13).
Fig. 13 The notes of Meroë WS 3 & 4 compared to the frequency of individual pitches in the extant ancient musical documents (labelled only in vocal notation).
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Fig. 14 The fingered part of Meroë WS4. Photograph: Stefan Hagel, courtesy MFA, Boston.

Fig. 15 The bell section of Meroë WS4. Photograph: Stefan Hagel, courtesy MFA, Boston.