Understanding the Aulos Berlin Egyptian Museum 12461/12462

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ZUSAMMENFASSUNG

Zwei graeco-ägyptische Gegenschlagzungenklarinetten aus dem Besitz des Ägyptischen Museums Berlin werden beschrieben und interpretiert. Auf beiden findet sich ein kleines Überblasloch; bei einer ist eines der Grifflöcher mit einem Metallring versehen. Vieles spricht dafür, dass es sich bei dem Paar um ein einziges Instrument handelt, einen aulós, *der in einer Reihe verschiedener ‚Modi' gespielt werden konnte. Parallelen zu anderen erhaltenen Funden weisen darauf hin, dass in der Antike Instrumente mit analoger Tonalität in verschiedenen Größen gebaut wurden. Anhand des Papyrusfragments eines Instrumentalstückes erweist sich schließlich, dass die erweiterte Modulationsfähigkeit des untersuchten Instruments ebenfalls dem traditionellen Repertoire der Auloshersteller zuzurechnen ist. Eine Reihe möglicher Skalen wird auf einem Nachbau exemplarisch vorgestellt.*

In 1894 two wooden pipes arrived at the Egyptian Museum in Berlin; they had been purchased on the antiquities market by the same person and probably together, apparently in Egypt. They were entered into the inventory with consecutive numbers, 12461 and 12462, and are still in the possession of the Museum. Both are currently on permanent exhibition, although not together: while 12462 remains in Berlin, 12461 was lent to the Archaeological Museum in Poznań. The pipes have seven and eight finger holes respectively, the second from the top of which is in both cases located on the side opposite the others. Pipe 12462 consists of two parts which are connected by a metal ring; one of the finger holes goes right through this ring (Fig. 12). Near the upper ends of both pipes, but at different heights, we find very small holes, which also extend into the main cavity. When acquired, 12461 was still equipped with a double reed, of which solely a drawing in the inventory remains (Fig. 13).

The items being unprovenanced, attempts at dating them were based on mere speculation. In the inventory they are classified as *„Geräte des mittleren und des neuen Reiches … Flöten aus Rohr, z. T. vielleicht später"* ("instruments of the Middle and New Kingdoms … made of reed, some perhaps of a later date"), which suggests a dating somewhere in the second half of the second or the first half of the first millennium BC, although in fact not excluding any later date. The museum database curiously assigned one pipe to the New Kingdom, the other to the Late Period. In contrast, Curt Sachs attributes both to the Greco-Roman period[1], which I have no doubt is correct, since the upper ends of the instruments exhibit the combination of a bulb with a conical reed insert that is so typical of ancient Hellenic and Hellenistic auloi[2]. Sachs classifies the objects as oboes, apparently with view to the double reed. This is however not unproblematic, since the shape of the main bore determines the nature of the produced sound in a much more fundamental way than does the type of the reed; and while the term 'oboe' suggests a conical bore, that of the two pipes is obviously cylindrical, like that of a modern clarinet. Thus, both modern instrument names are misleading, and it appears advisable to stay with the ancient 'aulos' (unless one would prefer to import a term from a culture where cylindrical double reed pipes such as the *duduk* survives).

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1 Sachs 1921, nr. 88–89.

2 A pipe of roughly similar make (Berlin Egyptian Museum inv. 16401, now lost: wooden pipe with bulb and insert cone, seven frontal and one dorsal finger holes; cf. Fig. 16) was found in Abusir-El-Meleq during the campaign of 1903. Rubensohn's excavation diary apparently implies a Greek context: *„Die griechischen Bestattungen finden sich alle direkt unter der Erdoberfläche"* ("underground Greek burials are all near the surface") (39); *„eine dicht unter der Erde liegende Mumie"* ("a mummy located underground close to the surface") (49); *„Unweit davon, aber nicht zu dieser Leiche gehörig werden 2 Stücke von einer (oder 2) Rohrflöte gefunden"* ("2 pieces from one (or 2) reed flute[s] are found nearby but do not belong to this corpse.") (52).

Sachs provides a photograph of the two instruments[3], and although he gives no detailed measurements, the questions he raises in his succinct description lay out the path for much of the present study. Apart from the dating, Sachs corrects the inventory description in three important points. Firstly, he observes that the material is wood, not *festes Rohr*. Secondly, he muses about the function of the small holes near the upper ends, proposing a possible use for sounding the upper registers ('overblowing'). Finally, he searches for an explanation for the metal ring, which he tends to regard as an ancient repair after the pipe had been broken, although he also considers the possibility that the ring was in fact a kind of 'key' mechanism (*„oder handelt es sich um eine Art Klappenvorrichtung?"*).

Sachs, who, of course, knew that auloi were typically double pipes, does not ponder the option that these two pipes might have belonged together. Why not? Presumably because they exhibit certain differences in their appearance. His description, however, does not hint at differences in material or colour (both pipes are described as being of *graubraunes Holz* [grayish-brown wood], as opposed to *dunkelbraunes Holz* [dark brown wood] for another find, no. 90 = inv. 16401)[4]. Possibly Sachs regarded the different shapes of the lower ends as ruling out a single instrument, since 12461 terminates in a slight bell, while the external diameter of 12462 even tapers down a tiny bit, with the bore remaining cylindrical – a divergence, however, which he does not mention (Fig. 14). So it was perhaps decisive that the finger holes look different, as Sachs noticed: while those of 12461 display neat smooth edges, those of 12462 give a much rougher impression (*roheingeschnittene Grifflöcher*/roughly cut finger holes). Indeed this is an undeniable contrast, but at the same time a puzzling one. The metal ring of 12462 testifies to experienced workmanship. If the ring was part of the original design, it is hardly conceivable that a production which involved such expertise in one respect would have tolerated sloppiness in another; and if it was not, it seems hardly more likely that such highly professional efforts would have been called upon in order to repair an instrument carelessly made and hence of obviously little worth. In short, a metal ring and uneven finger hole rims are difficult to reconcile, unless we assume that the state of the latter deteriorated – for whatever reason – only after the instrument was built in the first instance, metal ring included. But in this case, the difference in the shape of the finger holes forms much less of an obstacle to a one-instrument hypothesis.

A prima facie argument *for* a single instrument is its similarity to the Louvre aulos, which I have discussed in a previous volume of this series[5]. Unfortunately the Louvre aulos is also unprovenanced, but almost certainly from Egypt. Although it is larger, it resembles the present pair not only in general shape, but significantly in the fact that the position of the first hole from the top on the lower pipe corresponds to the fourth hole on the higher one. We will see below that this relates to a genuinely musical structural resemblance. On the other hand, the Louvre instrument has no metal ring, and its two pipes are of equal length and shape. At any rate there can now be little doubt that this was indeed one aulos, and the present discussion will in turn reinforce such an interpretation[6].

Before we proceed to a musical evaluation, however, let us complete the material description of the two pipes. As shown in table 1, the general measurements of the pipes such as their internal and external diameters and the ranges within which the longitudinal and transversal diameters of the elliptical finger holes lie, are very similar and cer-

	external diameter (straight part of tube)	main bore	finger holes $Ø_l \times Ø_t$
inv. 12461	12.45 – 13.45 mm	~ 7mm	5.9–6.6 mm × 5.4–5.9 mm
inv. 12462	12.40 – 13.20 mm	~7.25 mm	6.0–7.4 mm × 5.2–6.3 mm

Tab. 1 General measurements.

3 Sachs 1921, Taf. xi.

4 Now, that the instruments are separated, the similarity in colour is not easily ascertained; at any rate, in my photographs taken with the same digital camera I fail to detect a difference. – On Berlin Egyptian Museum inv. 16401 cf. note 2 above.

5 Cf. Bélis 1984; West 1992, 100–101; Hagel 2004.

6 The main argument against such an assumption is the great number of finger holes, exceeding the five or six that can be played with one hand. In Hagel 2004, 385 n. 81, I have considered the possibility that the instrument might have been prepared for the addition of a key mechanism but not completed. I no longer think this is a possible option. Different sets of holes were rather made available by stopping others with lumps of wax or wooden plugs (both methods work nicely).

tainly do not testify against their belonging together[7].

The most characteristic part of the pipes is their higher end with reed insert, bulb and certain decorations. When the respective elements are laid out side by side (Fig. 15), it is obvious that they do not give the impression of perfect identity. This is however only due to divergent curvatures; but the number and structure of the elements (cone, bulb, small anti-cone, thin band) are identical, and their positions are very nearly so. After all, the shapes of the higher ends of the two pairs are much closer to each other than to other remaining pipes (cf. the examples in Fig. 16). Thus, we must acknowledge that the similarities are more significant than the divergences, which makes the assumption of two independent instruments still less likely. In fact, the divergences are compatible with the assumption that the maker marked fixed distances from the end, but did not care about, or was unable to achieve, exactly similar angles or curvatures.

There is, however, a more substantial difference, although one hidden beneath the surface: on 12462 the enlarged diameter of the reed insert ends in a step, while on 12461 its connection to the main bore is smooth. Correspondingly, the cavity of the insert is practically cylindrical on 12462, with a length of 14 mm and a diameter of 9.5 mm (Fig. 17 and Fig. 18), while on 12461 its contour approximately follows the external cone, which entails a significant widening[8]. Obviously, the two inserts were produced with different techniques (on my replica I have worked out the cone with a small rounded file, while I had to build a specific guided drill for the stepped insert; cf. Fig. 19). I do not think there is a possible functional explanation for this difference. Its sole conceivable technical consequence is that the step can provide a fixed position for the reed, which the smooth cone does not. But this does not make any musical sense: in order to adjust not only the pitches but also the intervals of two pipes, it does not suffice to tune one to the other; one must fine tune the positions and/or properties of both reeds. So the conclusion is hardly avoidable that our two pipes were not made in the same workshop at the same time.

On the other hand, the present conclusion cannot eliminate the evidence of significant similarities and a common history (however little we know about it). On the contrary, the perfect resemblance of the decorative elements is even more surprising if contrasted with the dissimilar internal shape. How then can the seemingly contradictory evidence be reconciled? Up to now, we have met strong indications that the two pipes belong together, but also that they were not made as a pair. This is only possible under the assumption that one of them was manufactured as the complement of the other, presumably after its original partner was lost or damaged. Which one would have been the newcomer? More probably, the less sophisticated pipe, because it is less likely that a special effort would have been made to supplement the less complex half of an instrument. This suggests that 12462 with its metal ring belonged to the original pair. The assumption is in best accord with the different shapes of the inserts: a cone like that of 12461 is more easily produced, and the absence of a suitable drill would perfectly account for the fact that allowance was made for such a hidden divergence, while the structure and measurements of the visible details were rather accurately reproduced. This hypothesis also offers a potential explanation for the irregular shape of the finger holes of 12462, which are so puzzlingly at odds with the sophisticated metal ring: possibly the new complement pipe did not quite produce the required pitches, so that the owner felt the need to tamper with the size of the holes of his or her original (it is easy to enlarge a finger hole permanently, but not so easy to reduce its size). This is, of course, highly speculative; but it is important to show that the facts are compatible with a consistent view.

In the foregoing I have repeatedly stressed that the bronze ring with its hole, which as far as I know is hitherto without parallel on any wooden aulos, required the most advanced craftsmanship. Personally, I find it much more straightforward to drill and turn an entire new pipe on a lathe than to fabricate a seamless metal tube: the idea that such a ring is an ancient repair thus appeared to me as far-fetched from the outset. One of my first aims in having the pipe X-rayed was therefore to establish whether it was really broken. It soon turned out, however, that X-rays would yield no information about wood beneath a layer of metal of this thickness. Fortunately Mrs Margret Pohl from the Egyptian Museum kindly agreed to disassemble the instrument that her conservatory skills had made a seeming whole years before. What a glance through the finger hole had allowed me to guess beforehand then became obvious: beneath the ring the two wooden half-pipes meet with smooth rims (Fig. 20). Consequently, the repair hypothesis is

7 All measurements, of course, reflect the present state of the items. The wood may have shrunk during the past millennia, but since the pipes are still straight this effect was probably not strong and certainly not irregular; it may have a slight effect on calculations of absolute pitch, but I am confident that it can be neglected as regards questions of musical scale.

8 The inferred angles are practically identical: over a length of here also 14 mm, the internal diameter widens from ca. 7 mm to 11.5 mm, the external diameter from 10.8 mm to 15.4 mm, both corresponding to an angle of about 18 degrees.

entirely out of the question: wood never breaks smoothly. In fact, the pipe was either cut in two or, much more probably, manufactured from two separate pieces of wood from the outset[9].

Therefore, the ring was part of the instrument's original design, and, of course, its purpose cannot have been to hold two pieces of wood together. The conclusion is inevitable that Sachs' hesitant suggestion of a mechanism hit upon the truth: the ring must be a simple relative of the elaborate metal keywork that we know from expensive professional instruments from the Hellenistic and Roman periods, most prominently from Pompeii (for an example cf. Fig. 22)[10]. These have such rotating bands for all of their finger holes, delicate cylinders of bronze or silver, little more than 0.1 mm thick, gliding on similar cylinders that are fixed to a bone or ivory core. Our present instrument cannot compete with these exponents of the highest musical standards; but this must not obscure the fact that even its robust single ring (0.45 mm thick, presumably bronze) constitutes something of a feat for a flute maker. Firstly, the application of a seamless ring whose external diameter does not exceed that of the pipe is possible only if the pipe is composed of two parts that meet right beneath the ring and must consequently be glued together beneath the ring – a procedure that certainly compromises the stability of the instrument. Secondly, the ring must be perfectly round in order to be both turnable and airtight. Thirdly, an optimal fit around the wooden core must be ensured by some material that is mouldable, but does not cause too much friction. On top of this, since the volume of the wood changes with varying humidity – an inevitable problem in a mouth-blown instrument – it is desirable to reduce the wall thickness of the wooden core beneath the ring as much as possible, replacing it with some material that is not affected by humidity. Accordingly we find that the core beneath the ring is of significantly reduced diameter, and still partly covered with a darkish substance. Notably, this substance remains only on the wood and not on the metal. A pattern of incised grooves around the core obviously served to ensure a better hold (for an analogous technique used to attach a metal cover cf. the reed insert of the Pompeii instruments, Fig. 24); where the substance is now broken off this has usually happened along these grooves[11]. There was unfortunately no time to obtain a spectrographic analysis. In any case, the way the pipe was put together proves that the substance must have been in a viscous state when applied and hardened afterwards (presumably, the ring was turned from time to time during this process, so as to remain movable)[12]. Consequently, I do not believe that it could contribute much to the stability of the construction; it seems that most depended on the glue that held the wooden core together, at annular surfaces hardly more than 1.5 mm thick, and interrupted by the finger hole (cf. Fig. 23). All in all, we must conclude that only a significant musical gain can have prompted such a comparatively complicated construction: it must have been of special importance to open and close this particular finger hole quickly. At the same time, the presence of the ring proves beyond any doubt that the pipe was not meant to be played on its own, as a '*mónaulos*': both hands together would manage its eight holes most easily, so that the application of a mechanism would be absurd. Similarly, there would be no reason not to have at least one further hole for the small finger of the second hand, extending the scale downwards – if not also a second thumb hole.

This brings us to the musical evaluation. As stated above, of all published auloi it is apparently the Louvre aulos that bears the closest resemblance to the Berlin pipes. A concise summary of its tonal characteristics therefore provides the optimal background for the following investigation[13]. I have already mentioned that the highest hole of one of its pipes corresponds to the fourth highest on the other. In terms of pitch, this difference amounts to a fourth, in accordance with the heptatonic ancient Mediterranean music culture to which the instrument belongs. More specifically, the Louvre aulos relates to the so-called 'Greater Perfect System' of ancient Greek music theory (*sýstēma téleion*

9 The blackish substance described below precludes an examination of the grain of the wood right at the meeting point, but the visible texture otherwise suggests separately made pieces, which is confirmed by the X-rays: cf. Fig. 21. The same is indicated by the external diameter, which measures 12.7mm below, but 13.2mm above the ring; such a difference would be wholly unlikely had the tube been turned on a lathe in its entirety.

10 Cf. Howard 1893; Bodley 1946; Masaraki 1974; Hagel 2008.

11 The position of the grooves was apparently obtained by consecutively halving the distances; the groves seem to have been incised while turning the pieces on a lathe.

12 When reconstructing the pipe, I experimented with different types of resin available in the ancient world – rosin, sandarac, copal, frankincense and mastic – finally applying a mixture of the former four, largely based on rosin and partly charred during application. The procedure of filling the space below the ring without either burning the wood or gluing the ring down to it is also encumbered by the obligation to use only vertical flames for heating. The last additions and final shaping can only take place after the parts have been glued together, which makes it inevitable that they meet right beneath the hole – and explains why they do so in spite of the fact that this seriously diminishes the area where the two parts are in glueable contact.

13 For the following, cf. also Hagel 2005; here I modify some of the hypotheses about the Louvre aulos' capabilities, which, however, does not affect the overall conclusion – these are generally corroborated by the evidence discussed here.

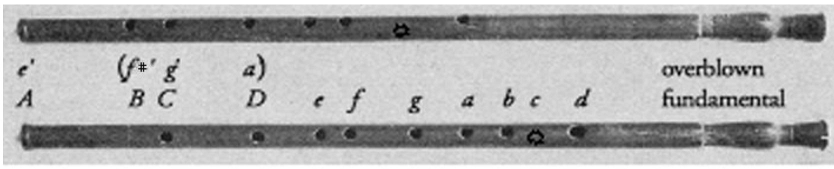

Fig. 1 The scale of the Louvre aulos (note names indicating relative pitch).

meízōn): with all finger holes closed, both its pipes sound their lowest note (*proslambanómenos*, conveniently transcribed in relative pitch as *A*); the highest note available on both is the central *mésē* an octave higher (*a*); the overall highest finger hole corresponds to the important *nḗtē synēmménōn*, again a fourth higher *(d*); while the top note of the 'central octave', the *nḗtē diezeugménōn* (*e*′) can be sounded by overblowing the fundamental *A* (cf. Fig. 1)[14]. All notes in between are accessible, although, of course, not all of them during the same performance: as stated above, different sets of finger holes must be pre-selected by means of plugs.

The 'Perfect System' contains a still higher tetrachord from *e*′ up to *a*′, whose status as an addition is evinced by its designation as *hyperbolaîon*, 'cast beyond'. Not all of its notes, however, can be played on an instrument of the design of the Louvre aulos: owing to the physics of cylindrical pipes, overblowing yields only the odd harmonics, and thus the twelfth above the fundamental in the first instance. A twelfth being an octave and a fifth, the series of overblown pitches is thus shifted to the neighbouring key as compared to the original. In particular, the *B* hole would yield not the required *f*′ but an *f* sharp. It would not only be extremely difficult to flatten this pitch by an entire semitone – this cannot be done so far down the tube by means of embouchure, but only by partially covering the finger hole – and such an attempt would also so severely compromise the tone quality that the note would hardly be perceived at all when sounded together with any note from the other pipe. Thus, the actual usage of an *f*′ on the Louvre aulos must apparently be excluded. In other words, it can only play straightforward diatonic melodies up to *e*′; any further upward extension of its range would either remain pentatonic, or modulate into the neighbouring key.

On the Louvre aulos, the uneven spacing of the finger holes is evident at first glance, so that one can easily discern what a musical analysis confirms to be tones and semitones. On the Berlin pipes the differences are a bit less pronounced, but even this way it is clear that a differentiation between scalar steps of more than one size is intended (cf. Tab. 2). This fact also associates the items with the Greek aulos, setting them apart both from the Ancient Egyptian reed double-pipe and from modern related instruments such as the *duduk*. Their finger holes, by the way, were smoothed out not only at the surface, in order to facilitate sealing them with the fingers, but also in the interior, where a removal of the sharp edges optimises tone production. The reason why the finger holes are a bit more evenly distributed than they are on the Louvre instrument is primarily to be sought in the smaller size of the Berlin pipes, resulting in generally smaller inter-hole distances. Here it was necessary to preserve a certain minimal distance, reflecting the breadth of the player's fingers: when I play the replica, my fingers do not quite come into contact with each other at the crucial points.

A replica, as I have argued previously (and others have before me)[15], is, however, not the best way to determine the intended pitches of an aulos. Apart from the practical inconveniences involved in experimenting with different sizes of reeds, the unconscious efforts of any player to produce a familiar scale present a real obstacle. If possible, an evaluation should therefore start by determining an 'ideal' scale by means of calculations based on the instrument's layout; as a second step, a replica is of course most welcome to confirm the conclusions. In the present case, the unusually well-preserved state of the pipes makes the calculations straightforward; the only open parameter, the effective size of the reed, can only vary over a few centimetres. For the evaluation I have used the software described in the course of the evaluation of the Louvre instrument; although I have developed it further over the past six years, the basic principles and algorithms remain unaltered[16].

It emerges that the pipes produce optimal results, each in itself as well as the two together, on the assumption that 12461 was equipped with a reed of an effective length of 3.2 cm, and 12462 with one of 4.3cm (Fig. 25 and Tab. 3). It must be stressed that the effective length of a double reed

14 When transcribing ancient notes into modern note names it is useful to change from uppercase to lowercase letters, and further to letters with strokes, not at *c* as usual, but at *e*, reflecting the ancient tetrachordal structure. Lowercase letters thus denote the 'central octave' (with the inevitable exception of *e*′).

15 Cf. Landels 1981; Hagel 2004, 373–374.

16 Cf. Hagel 2004, 380–381.

Pipe 12462		
no.	size (mm) $\varnothing_l \times \varnothing_t$	distance from lower end of pipe (mm)
1	7.4 × 6.3	102.8
2	7.4 × 6.3	127.8
3	7.1 × 6.1	147.1
4	7.3 × 5.4	171.8
5	6.7 × 6.4	194.3
6	6.5 × 5.2	211.0
7	5.9 × 5.6	221.0
8	6.0 × 5.5	238.0
small hole		309.0

Pipe 12461		
no.	size (mm) $\varnothing_l \times \varnothing_t$	distance from lower end of pipe (mm)
1	6.0 × 5.8	31.8
2	6.0 × 5.9	49.8
3	6.4 × 5.6	82.0
4	6.4 × 5.8	107.8
5	6.0 × 5.4	125.8
6	5.9 × 5.8	150.8
7	6.6 × 5.9	175.3
small hole		280.7

Tab. 2 Finger hole measurements.

Between pipes 12461 and 12462			
interval	hole on 12461	hole on 12462	dev.
1/1	3	1	+13
1/1	4	2	+10
1/1	5	3	+19
1/1	6	4	+15
1/1	7	5	+1
2/1	7	0	+11
3/2	2	4	–15
3/2	3	5	+10
3/2	7	1	–4
3/2	4	6	–1
3/2	5	7	–15
4/3	3	0	+1
4/3	2	3	+6
4/3	3	4	+9
4/3	6	1	–19
4/3	6	7	+1

Within pipe 12461			
interval	hole 1	hole 2	dev.
3/2	0	5	+16
3/2	3	7	+9
4/3	2	5	–14
4/3	3	6	–6

Within pipe 12462			
interval	hole 1	hole 2	dev.
2/1	0	5	+11
3/2	0	2	–19
3/2	1	5	–4
3/2	2	6	–11
4/3	0	1	+15
4/3	1	4	–4
4/3	4	7	–13

Tab. 3 Calculated resonant intervals. Finger holes are counted from the lower end of the instrument, with '0' representing the tube with all holes closed. Intervals are labelled by ratios of frequencies: 1/1 = unison; 2/1 = octave; 3/2 = fifth; 4/3 = fourth; 'dev.': calculated deviation from pure interval (up to ±20 cents).

mouthpiece may differ significantly from its physical length, owing mainly to its non-cylindrical geometry; that required different effective lengths need not reflect a similar difference in physical length is in accordance with literary evidence[17]. Nevertheless, it is worthwhile to compare the predicted effective lengths with the drawing of the original reed of 12461. Since the sketch is not to scale, we have to rely on the assumption that the proportions are at least halfway correct. However, a comparison of the illustration of the upper end of the pipe, which appears next to that of the reed in the inventory, with a photograph demonstrates that the representations are, although certainly not excellent, still accurate enough for the present purpose (Fig. 26). Unfortunately, the exact appearance of the mouthpiece end that went into the tube is unclear: was it originally drawn as a cylinder and subsequently corrected to a slight taper, or was it perhaps the other way round? In any case, the ratio of the reed's overall length to its diameter at its cir-

17 Theophrastus, *Hist. plant.* 4.11.7, describes how adjacent parts of cane stems are made into a matching pair of aulos reeds; since he records which part of the stem goes into which pipe, it is clear that they had different properties, and that these were reflected in the design of the pipes. The optimal effective lengths for the Louvre aulos differ by 4 mm; cf. Hagel 2004, 382. In the present case, however, we must note the peculiarity that the higher pipe gets the reed with the greater effective length.

	tube		finger holes									
inv. 12461		0	1	2	3	4	5	6	7			
		223.2	241.2	255.5	283.5	313.4	338.0	376.7	427.5			
inv. 12462	0				1	2	3	4	5	6	7	8
	212.4				285.6	315.1	341.8	379.9	427.6	469.8	502.6	556.8
	A+3	*B* ^{b}	*B*+23	*C*+22	*D*+2	*e*–15	*f*+6	*g*+8	*a*+12	*b*–25	*c*–8	*d*–31

Tab. 4 The scale of pipes 12461 and 12462. Deviations in cents from an equally tempered diatonic scale (Aristoxenus' *diátonon sýntonon*) based on relative '*A*' = 212.0 Hertz (Note that the coincidence with modern 'Classical' concert pitch is, well, coincidence.).

cular opening lies between about 5.6 (straight) and 6.0 (tapering). If we make the reasonable assumption that this opening corresponded closely to the opening of the pipe's insert where the reed ended, we must expect that it actually measured between about 7 mm (the reed extending into the pipe for the full 14 mm of its conical insert, in correspondence with the step at 14 mm on pipe 12462) and 8 mm (with only about 11 mm of the reed entering the pipe). From a combination of these assumptions we obtain minimal and maximal values for the overall reed length and consequently for its physical length outside the pipe: the latter would have been somewhere between 2.5 and 3.7 cm (Fig. 27 shows an intermediate solution resulting in an extension of 3 cm). This is, after all, in good accordance with the theoretical effective length. Of course, this estimate, into the calculation of which there entered so many uncertainties, cannot claim to provide a confirmation; it is only intended as a proof that the evidence from the reed by no means contradicts our results.

Table 4 displays the calculated frequencies, indicating the differences between the resulting scale and an equally tempered diatonic[18]. In a couple of cases, indicated by shaded fields in the table, the printed pitches are, however, based on insufficient evidence or a slightly misapplied algorithm: firstly, since the tube of 12461 widens at its end, the corresponding pitch cannot be accurately calculated. Secondly, the exact size of the finger hole beneath the metal ring can no longer be determined: because the wood is so thin at this point and the hole is divided between the two parts of the pipe, its rims have partly deformed. Nevertheless, the calculated pitches are in best accordance with those produced from a replica[19]. Thus a (slight) uncertainty remains merely for the hole beneath the ring, which I naturally made of the same estimated size on which the calculation is based. In practice, the intended pitches for the highest hole(s) may also diverge from the calculation, just because these are most strongly affected by reed effects and can most easily be adjusted by means of embouchure, i.e. altering the position of the reed in relation to the lips, or the pressure exerted on it[20].

As regards the scale, we can only say that it is evidently heptatonic and diatonic. The specific theoretical intervals are not systematic in any way that would suggest speculation about a specific diatonic 'shade' as described by ancient theorists. But this is only to be expected for such a small and therefore high-pitched instrument, where the distances between the finger holes are partly co-determined by requirements imposed by the finger size. Without doubt, the *exact* rendition of melodic and especially 'harmonic' (i.e., inter-pipe) intervals depended a good deal on the player, in accordance with ancient literary evidence[21].

Expressed in relative notation, i.e., transposed to the white keys of a piano, the basic scale ranges from *A* to *d'*, over an octave plus a fourth: in terms of the ancient system, from *proslambanómenos* to *synēmménē*. In this respect our instrument is identical to the Louvre aulos, although pitched about a minor third higher. It seems therefore that largely similar instruments could be built at different pitches, a concept that we associate with the 'trans-

18 For the calculation it is always assumed that beneath the highest open finger hole all others are open as well. A different assumption would result in a minimal flattening, especially for the holes with a neighbour only a semitone below, and once more for the highest holes. Cross-fingering as we know it on modern woodwind is generally useless on auloi, because of their large finger holes in relation to the bore. For the complications that entail on a chromatic instrument cf. Hagel 2008, 58.

19 After my presentation of the present findings at the ISGMA conference, I was asked for a comparison between the calculated pitches and those that my replica plays. Surprisingly, I had not considered in advance that such a presentation would be almost compulsory. So I simultaneously played the calculated frequencies from the computer connected to the hall's audio equipment and one of the pipes. The practically perfect unison was appreciated by the audience; for the highest finger holes of the higher pipe, however, I had to point to the fact that they can easily be varied over a comparatively large range of pitches.

20 As my experiments have shown, it is indeed possible to apply different lip pressures to the two reeds of a double-reed double pipe instrument. With well-adjusted reeds and some experience this technique allows changes between fundamental and overblown notes on one pipe while remaining in the same register on the other.

21 Cf. Plato, *Philebus* 56a; Aristoxenus, *Harmonics* 2.41–3, p. 52.9–53.16 Da Rios.

posing' instruments of modern music, such as recorders and clarinets. Aristoxenus' classification of auloi in five sizes but without associations to different cultural environments might point to a similar approach; unfortunately we lack the context[22]. We will come back to the implications of such a 'transposing' class of instruments below.

On the other hand, the present pair of pipes is certainly more complex than the Louvre aulos: not only because it incorporates the simple mechanism of the ring, but also, because the lowest notes of the two pipes are dissimilar, 12461 apparently providing a modulating low $B^{\flat}$. It is essential to understand that this $B^{\flat}$ entails a modulation not only when the pipes are considered to be a pair, but also within 12461 alone, where $B^{\flat}$ adds another semitone below the one between *B* and *C* (interpreting '$B^{\flat}$' as belonging to the primary scale and '*B*' as modulating is, of course, also possible; but this would turn the relative '$B^{\flat}$' into a relative '*f*', whose appearance at the bottom of a stand-alone scale is apparently meaningless in the context of ancient music). The presence of $B^{\flat}$ is all the more noteworthy if one considers the fact that it replaces the regular *A* found on 12462 and both Louvre pipes, the *A* that represents the lowest note of the ancient 'Perfect System', *proslambanómenos*, an octave below its central note *mésē* (notably the top note of pipe 12461), in the tonal importance of which it is therefore to be expected to participate. To be sure, ancient theory incorporated the modulation from *b* to $b^{\flat}$ in the higher octave right within the standard of the 'Perfect System', but no similar provision was taken in the lower part of the scale. In short, no explanation would suggest itself for the omission of *A* in favour of $B^{\flat}$. We must conclude that pipe 12461 also cannot be understood if interpreted as a *mónaulos*; it seems to call for a counterpart that includes the low *A* which it lacks, a counterpart, that is, exactly like 12462. Thus, the chances that these two pipes appeared together by coincidence practically drop to zero, especially considering the fact that, as we have learned from the comparison with the Louvre instrument, the general layout could be adopted for more than one pitch standard. Consequently, I regard the conclusion as safe that a set of two pipes, each of which declares itself as belonging to a pair and which complement each other in exactly the expected way, was already used as a pair in antiquity.

Let us pause here for a moment and return to the divergence in outer appearance. We have seen that the different inserts can be accounted for by the theory that pipe 12461 was deliberately produced to match the valuable 12462; but this does not explain the dissimilar tube ends, where the slight bell of 12461 contrasts with the straight end of 12462, which is decorated with an incised line about 17.5 mm above. Must we finally resort here to the assumption that two pre-existing pipes have been recomposed into a new instrument? I think, not necessarily. The problem of the incised line is most easily disposed of, since it is nicely paralleled on the Louvre aulos, where a similar line on one pipe occupies the position of the lowest finger hole on the other, apparently to achieve some sort of visual balance (cf. Fig. 1 above). A similar explanation might apply to the differing ends of our pipes. Assuming that one pipe had to be 'shorter by a semitone', how could maximal visual balance be restored? Quite possibly, this could be achieved by adding weight to the end of the shorter pipe in another way, namely by increasing its width slightly, while, even more slightly, tapering the end of the longer pipe. This in turn has the additional advantage that the resulting 'bell' on the shorter pipe could be turned into a real bell by widening the internal bore also, from 7 mm to about 9 mm at the exit. As a result, the tone becomes higher than it would be with a straight bore, and consequently the pipe with the bell can be longer than a similar pipe without a bell – again perfecting the visual impression. So the apparent difference might in fact be a means to achieve maximal similarity. This is, of course, speculation – at any rate, the reader is invited to judge the effect from figure 14, where the photographs of the pipes are mounted as if their upper ends would coincide.

But why did one pipe have to be shorter, in the first place? Would it not have served quite the same purpose to make them equally long, but drill an additional finger hole for the required $B^{\flat}$? In fact there are two possible objections to such a design. Firstly, a finger hole that close to the end of the pipe was probably not considered to be aesthetically satisfying (it would have to be placed about where the incised line sits on 12462). Secondly, there is a pronounced difference between the sound of notes elicited from a finger hole and those from the end of the pipe. Therefore, the design we observe here is clearly to be preferred if the sounds

22 Aristoxenus ap. Athenaeus, *Deipnosophists* 634e.: "πέντε γένη εἶναι αὐλῶν, παρθενίους παιδικοὺς κιθαριστηρίους τελείους ὑπερτελείους" ("… that there are five sorts (*génē*) of auloi: girl, boy, *kitharisterian*, grown-up, over-grown-up"); cf. also Aristoxenus, *Harmonics* 1.20–21, 26.8–27.1 Da Rios; Aristotle, *Historia animalium* 581b (clarifying that παιδικούς refers to boys); West 1992, 89–90. Such an interpretation leaves open the possibility that each of these sizes could in turn accommodate instruments of different tonality; if it is correct, '*kitharistḗrios*' would refer to a size of auloi whose pitch range coincides with that of the concert lyre, facilitating performance together with the stringed instrument, but not making it the prime purpose of this aulos type.

from the two pipes with all finger holes closed were meant to be used in a similar function. What function might this be?

With a view to modern ethnomusicological parallels, many will at once associate such low notes with drones[23]. Such a possibility must certainly be considered for the *A* of 12462. The $B^\flat$ of 12461, on the other hand, is hardly a good candidate for a drone, given the fact that the higher part of the scale includes the natural *b*; and even if here a modulation is achieved by half-stopping the respective hole, the resulting $b^\flat$ is of such little prominence in the ancient system (where it is termed *trítē synēmménōn*), that its occasional appearance hardly justifies a drone note an octave below. Little evidence can be adduced for ancient bass drones anyway; on pipes with many finger holes like those under consideration it would be especially awkward if one hand were confined to hold its pipe during entire passages[24].

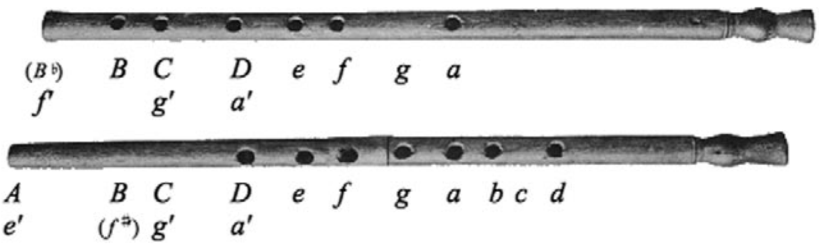

Fig. 2 The 'Greater Perfect System' on inv. 12461/12462.

But there is a more promising option. Above, we regarded the possibility that the low *A* of the Louvre aulos was overblown to an *e′* that complements the scale at the top. Actually the fact that cylindrical pipes overblow to the twelfth apparently explains why such instruments contain finger holes up to but not exceeding the eleventh. At the same time we have seen that on the Louvre instrument a further extension of the scale beyond *e′* lacks the natural *f′*, producing an $f^\sharp$ instead. The obvious solution is also to have a low $B^\flat$, which overblows to the required *f′*. But where to put this $B^\flat$? One might naturally assume that we want to have it at the same pipe as the *A*, so as to produce the two adjacent notes from the same pipe. But this is impossible if the overblown notes are to appear in melodic sequence with their lower neighbours – which is, of course, their most natural use. The reason is that in order to proceed from *d* to *e′*, for instance, one must inevitably close the *d* hole; accordingly, the hand is situated high on the pipe, and cannot then cover and subsequently open a low $B^\flat$ hole at the same time. Consequently *e′* and *f′* can only be played, if at all, on different pipes. Most naturally the *e′* is assigned to the same pipe that plays the *d*: this way the melody only needs to change between the pipes if it rises above *e′* (otherwise it would have to switch both between *d* and *e′* and between *e′* and *f′*). Since overblown notes tend to be softer than their fundamental counterparts, it is furthermore a good idea to produce the high *f′* not from a finger hole, but from the tube end, which gives a stronger sound. As a result the 'higher' pipe in terms of finger holes also becomes the 'lower' pipe with a view to tube length, exactly as we observe on the Berlin aulos. So we can project the entire 'Greater Perfect System' onto the Berlin pair (Fig. 2) – although, of course, always bearing in mind that only part of it could be employed in the course of a single performance.

The resemblance to the Louvre aulos appears to warrant the assumption that the more general layout – a diatonic scale from *A* up to *d*, with the highest *a* on the second pipe – was widespread. As we have seen, a low $B^\flat$ on the lower pipe is a logical refinement of that design. But was it also widespread? At first glance such a question may appear absurd, given the fact that only a single instrument of this type is known. Nevertheless it can be answered, thanks to evidence of a different kind. Only a decade ago, a papyrus fragment from the Michigan collection with musical notation was published; it belongs to the minority of ancient documents featuring instrumental music and is notated in the 'Lydian' key, with modulation to the neighbouring key in each direction[25]. The small scrap contains the remnants of four lines, no more than six to ten notes being legible in each (Fig. 3). Nevertheless two important points emerge:

23 For speculation on aulos drones, cf. Byrne 2002.

24 Note that this argument does not apply to Byrne's suggestion of a drone that alternates between the pipes, which take over the melody in turns. In the present case however, the pipes share no note lower than *D*, which excludes this particular type of alternating drone for the lowest notes.

25 Pap. Michigan 1205: Johnson 2000; DAGM no. 61 (dated to the first to third century of the Christian era). Actually the distinctive Lydian *diátonos* (ꓶ) is missing, its pitch appearing only in Hypolydian environment as ⊻ (once, after K). But this is probably coincidence.

Fig 3. The melody of Pap. Michigan 1205 (DAGM no. 61).

Firstly, its highest note is *e′*, and it is distinguished from all the others by the fact that it appears in all four lines, however different these are in their melodic range: in the first line, the melody moves between *e* and *a*, plus *e′* a fifth higher; the second line holds notes between *f* and *b*, plus *e′* a fourth higher; in the third line we encounter a continuous scale from *a* up to *e′*; finally, the last extant line runs from *a* down to low *B♭*, but again with the inclusion of *e′* one fifth above its otherwise highest pitch. Consequently, *e′* is most often connected to its melodic neighbours by large intervallic jumps; within this small sample we count no less than three major sevenths. As far as I can see, this is a unique characteristic of this fragment; in no other ancient musical document does a single note acquire a comparable state of splendid isolation. The foregoing considerations however show that this phenomenon finds a natural explanation if it is assumed that the piece is intended for an instrument similar to the Louvre and Berlin auloi, where the *e′* is the (first) overblown note, produced in a totally different way than its neighbours lower in pitch. It is no wonder if this difference in execution leads to a difference in melodic usage as well. As regards questions of fingering, it is certainly not more difficult to close the entire row of holes when playing in a low range (where the higher holes are closed anyway).

Secondly, the fragment terminates with a run of notes that is highly surprising from a solely music-theoretical point of view. In spite of completing the descending sequence of *f – e – D – C*, in the Lydian key, with the expected *B* (or perhaps an *A*), a third whole-tone step introduces a modulating *B♭*. If we want to describe this modulation within the framework of ancient theory, we find that it is considerably less conveniently accounted for than the respective modulation an octave above (as found at the start of line 3 of the fragment). There the model system provides the so-called *synēmménon* tetrachord, which allows switching between *b* and *b♭* without involving the notion of a change of key. Alternatively one could also talk about a modulation from Lydian to Hyperlydian; even so, the introduction of merely a prefix displays the familiar nature of such a melodic movement. In the lower octave, in contrast, we leave the realm of the 'Lydian' altogether: within the system of keys, the note in question only turns up in the Hypophrygian and Phrygian (cf. Fig. 4). It ought to be said that Hypophrygian is effectively nothing other than the downwards prolongation of Hyperlydian; but this must not obscure the fact that from the viewpoint of ancient scalar theory the cases are very different. Obviously, the notated melody does not let theory constrain the natural flow of its modulations[26].

In contrast to ancient theory, the Berlin instrument makes the final *B♭* appear quite natural, the downward movement terminating (I think) at the

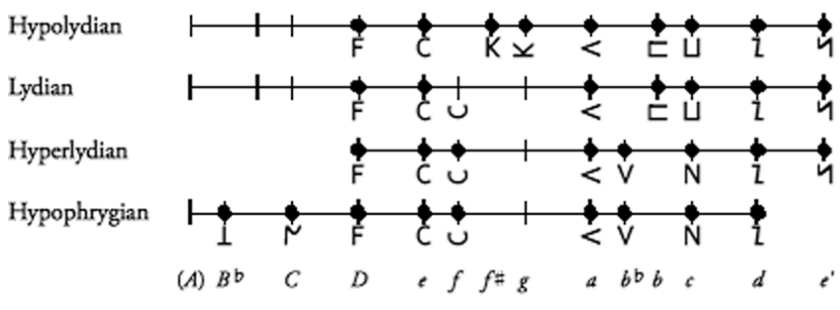

Fig. 4 Notes and scales in Pap. Michigan 1205 (DAGM nr. 61).

26 Compare the jump from Ч to N in line three, which also crosses the boundary that theory erected between Hyperlydian and Hypophrygian, the two scales that represent the same 'key' in a modern view. On the other hand, it must be emphasised that the writer is in perfect command of theory: the final modulation is correctly foreshadowed by already notating the preceding 'C' as Hypophrygian Ͷ, not Lydian L.

lowest note the lower pipe could play – that pipe, notably, which alone provides the notes for the downward movement at all. A consideration of the typical restrictions involved in playing similar auloi leads to a better understanding of how the inclusion of the low $B^\flat$ very probably became a commonly employed melodic option. We have seen that the origin of the respective instrument design almost certainly was the desire for a high f', as required for the correct upward extension of the basic scale. Whenever a particular fingering position and combination of available and plugged holes made this f' available by overblowing the $B^\flat$, this $B^\flat$ was, of course, also available, by *not* overblowing. The absence of an extended mechanism – very likely many instruments of that type did not even have the single ring we find on 12462 – ensured that the accessible range and selection of notes within one piece was always limited. We must all the more expect that musicians availed themselves of all possible notes. If the natural *B* had to be plugged in order to access a regular f', why not enrich the piece by an occasional $B^\flat$? In this way that particular modulation would soon have established itself as a common feature of aulos music, also employed in compositions where f' plays no (important) role.

On the basis of the concurrent evidence of the status of e' and the appearance of B^{b}, I regard it as safe to conclude that the Michigan papyrus holds music for the aulos; more specifically, for an aulos some of whose fundamental characteristics are similar to those of the Berlin pair. Of course, it would be foolish rashly to assume an all too close connection: plausibly there were instruments of various sizes, layouts and professional levels that shared the required features. In this context we must return to the question of absolute pitch and its notation. The Berlin pipes would by no means play the notes of the papyrus, if these are understood as absolute pitches referring to the full system notational keys, which apparently imply a fairly consistent pitch standard[27]. On the other hand, it would actually be difficult to play the melody on any aulos built according to that standard, because the required much lower pitches would bring about uncomfortably large distances between the finger holes, manageable only on professional pipes equipped with turning metal bands throughout. On balance, I think it is most probable that the Michigan papyrus is not pitch-specific – after all, the pitch standards have been inferred mainly from documents with the 'vocal' variant of the notation – but rather an example of scores written for 'transposing' instruments, where the natural Lydian scale corresponds to the basic scale of the pipe, the Lydian *proslambanómenos* being equated with the low '*A*'.

Returning to the Berlin pipes, we must next examine the musical significance of the ring, whose position apparently marks the most important switch between different tonal options. Situated at the sixth hole from the top of 12462, it covers – and uncovers – the first hole that is not operated by a finger in the highest and most important playing position on this pipe, the position that avails itself of the thumb hole. The ring thus defines the lowest note in this position, the note played when all five fingers close their holes. If it is in 'open' state, one obtains a (functional) *f*. If it is turned to 'shut' the *f* hole, on the other hand, the lowest note becomes *e*, or, if additional finger holes are plugged by some other means, *D* or *A*.

For an evaluation of these options it would be important to know whether the ring was merely turned between single pieces, or also during performance, as were the related rings of professional instruments. Unfortunately the evidence is not decisive. The sleeves of expensive pipes were equipped with small knobs which the fingertips pushed upwards and downwards. Without them, the operation of the mechanism would have been much more difficult, if not impossible. Although we cannot establish details, the amount of friction between the metal tubes being unknown, it is obvious that pushing a polished surface relying solely on skin friction is impractical and might become impossible if sweat is involved; moreover, the knobs also provided the player with an invaluable point of orientation, both tactile and visual, revealing the position of the individual rings. Now the ring on 12462 not only has no such knob, but also shows no traces of one formerly soldered to its surface (such traces are visible on the Pompeii pipes even after they have been cleaned and newly polished; cf. Fig. 28). On the other hand, the mere effort of adding the ring, and that this was done although the construction compromised the stability of the instrument, speaks in favour of a function during performance. Another indication in this direction is the fact that the ring extends upwards almost up to the next finger hole, just as if it were made for easy operation by the small finger. On my replica, it was only sometimes possible to turn it this way while playing, depending on the humidity of the wood. On balance, I cannot currently decide this question. The ancient makers had, of course, much greater skills and experience than I have (and better-suited wood, no doubt), so the technical problems are probably not insurmountable. On the other hand, the absence of any handle is difficult to explain.

[27] Cf. West 1992, 273–276; Hagel 2009, 68–95. The following is argued in more detail in Hagel 2009, 333–344.

In any case, as the reader will have noticed, even if the mechanism were regularly operated also during performance, it provided no straightforward extension of the melodic scale. In order to turn the ring, the small finger inevitably had to be removed from its own finger hole. As a consequence, sequences such as *e – f – g* or *g – f – e* could not be played, only *e – g – f*, *f – g – e* etc. So it is very probably safer to think about the ring not so much as a melodic device than as a kind of 'mode switch', which is the sole option anyway if one only believes in an operation between pieces: its function was primarily to give access to different *sets* of notes, along with the ensuing intervallic possibilities.

What might be the meaning of the respective sets? With the ring closed but the lower holes unplugged, we have said, the scale of 12462 runs as follows: *e – g – a – b – c – d*, diatonic in the higher but anhemitonic pentatonic in the lower part. In the context of ancient music, it is easy to see what is gained thereby: by excluding *parypátē* (*f*), a note of comparatively small modal importance, one obtains access to *hypátē* (*e*), a typical focal and final note and part of the primary harmonic structuring of the central octave: *e – a – b – e′* (cf. Fig. 5 for the relative frequencies of occurrence). So the aulos can perform in a traditional *A/E* mode as known mainly from Hellenistic documents[28].

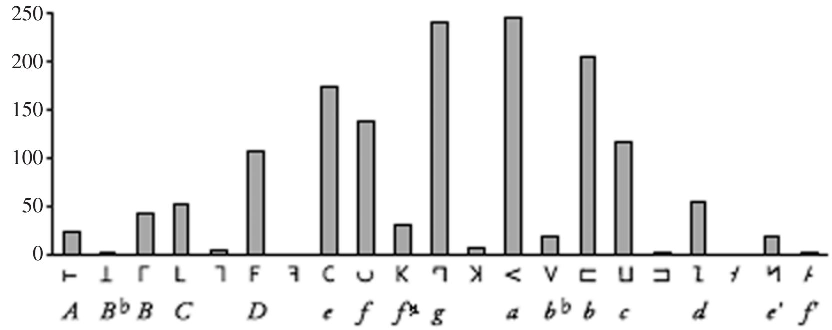

Fig. 5 Frequency of notes in ancient musical documents in the Lydian key (vocal and instrumental).

If the ring is opened, on the other hand, *e* is out of reach (always assuming the main playing position, which includes the thumb hole), and the instrument will not as easily lend itself to an *A/E* mode. Instead, the now available *f* can serve as a convenient lower leading note to *g*. This fits the *G/D* mode that apparently came into vogue in the Roman period[29]. Consequently I suggest that the two positions of the ring were connected with these two different 'modes' (or perhaps rather: superclasses of modes).

It remains to explain how the small holes near the upper ends of the pipes were used. My experiments have shown that Sachs was obviously right in his suggestion: they serve the purpose of 'speaker' or 'register' holes very well, facilitating or even enforcing the production of the upper harmonics (the principle behind speaker holes is to introduce a small air leak at a suitable position along the oscillating air column that destabilises the longest sound waves, so that those of higher frequency can take over). I think it is for the first time that we can thus regard Howard's old hypothesis of the *sýrinx* being a speaker hole as archaeologically corroborated and experimentally verified[30]. Moreover, my experience with the device has led me to the conviction that it probably was no simple on-off switch. The Michigan papyrus has shown us that we must reckon with varying demands, especially to overblow one pipe but not the other. If the *hyperbolaîon* tetrachord as a whole really played a role on instruments like ours, it would call for a pipe that overblows much easier than it does in pieces staying in the lower range. Finally, the playing style called *syríttein* obviously employed overblown notes throughout, presumably in an even higher register than used for the *hyperbolaîon* notes[31]. In the face of such a variety of requirements, it is obviously of considerable help if the respective sensitivity of the pipes to overblowing can be adjusted. In practice, this is done by fine-tuning the size of the leakage. Small though the *sýrinx* holes are on the Berlin pipes, if they are entirely opened, the production of most notes in the basic register becomes practically impossible[32]. But there is an easy and effective procedure for adjusting the hole size: after placing a tiny lump of wax at its edge, one cautiously squeezes it by

28 Cf. West 1992, 187.
29 Cf. West 1992, 187–188; Hagel 2006, 303. Note also that the finger holes of 12462 run from *D* to *d*, and that it never makes sense to plug the *D* hole on 12461.
30 Howard 1893, 32–35.
31 Hagel 2005, 86–89.
32 Apart from the degree of air-tightness this also depends on the softness of the reed: the stiffer it is, the more the instrument tends to produce the higher modes.

rolling the thumb over it. This way, the diameter is repeatedly reduced by tiny amounts until the pipe responds in the desired way. By the way, the surface around the speaker holes is slightly indented, which provides a better grip for the wax (cf. Fig. 26).

The positions of the *sýrinx* holes on the pipes are markedly different: that of 12461 is placed on the straight part of the tube, about 5 cm from the upper end of the pipe, while that of 12462 is drilled right through the bulb, at a point only 3cm from the opening. This difference makes good musical sense: since the finger holes of 12462 go higher up the tube, the optimal placement of a speaker hole (which is always a compromise between the various optimal positions for all the notes to be overblown) must be higher as well. I will come back to this topic on another occasion.

The preceding interpretation of the artefacts has suggested a number of hypothetical modes of how they might have been put to use, involving various combinations of holes either fingered, or plugged, or serving as vent holes, as well as different uses of the speaker holes. In the following I proceed to prove the practicability of such an approach with a selection of important examples played on my replica (Fig. 30). The corresponding recordings are found on the CD that accompanies this volume. It is, of course, not my contention that these resemble the sounds that an ancient musician would have produced after several years of training with an experienced master: I had to re-invent not only the playing technique but also that of reed-making in a very short time. But if an unskilled player such as I can elicit the desired scales from the pipes, I think we can be confident that the ancient professional would not have been content with less. Similarly, I have used circular breathing for all the recordings. Even if some might be less confident than I am that this technique was paramount for much of ancient aulos music, it should be clear that whatever is possible with circular breathing is also possible without, while the opposite is not true.

I start with the simplest configuration: all finger holes open, except for the register holes (Fig. 6). This way the ninth from *C* up to *d* is accessible, the scale of the two hands overlapping within the third from *f* to *a*. As discussed above, this arrangement is especially suited to a *G* mode, with *f* as a leading note to *g*, and *g* possibly serving as a 'swapped' drone: a note common to both pipes sounds continuously even though the melody moves from one pipe to the other (Track 1)[33].

With the metal ring turned to shut its hole, we obtain *e* instead of *f* as the lowest note of the higher pipe, the overall scale remaining identical (Fig. 7). Thus, the instrument would be suited for the apparently earlier *A/E* mode (Track 2, with 'swapped drone' on *e*, and Track 3, with drone on *a*).

By sealing the two highest holes on 12461 with wax, the scale can be extended downwards to *B*,

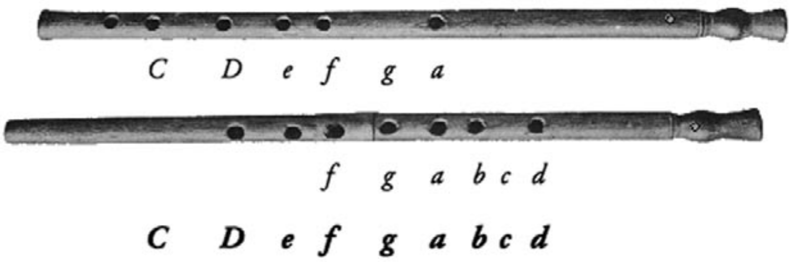

Fig. 6 'Simple *G/D* mode'.

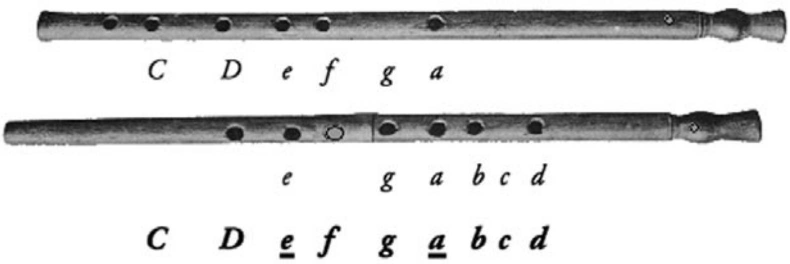

Fig. 7 'Simple *E/A* mode'.

33 Cf. Byrne 2002, 368 with musical Example 2.

thus completing the tetrachord *hypatôn* of ancient theory. It is advisable to leave the ring in a 'closed' state, so that we get the structurally important *e* (*hypátē mesôn*) as the single remaining common note, and not the harmonically marginal *f* (*parypátē*, standing at a tritone to *B* and *b*). The range is now a minor tenth (Fig. 8; Track 4).

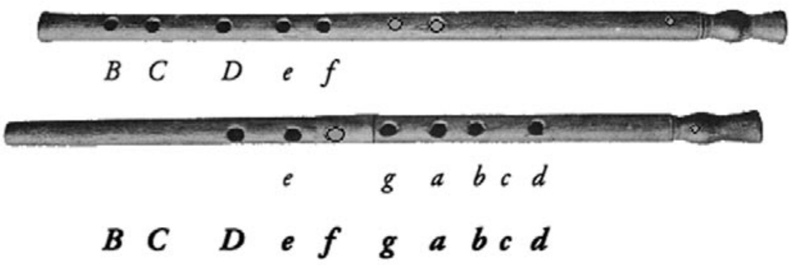

Fig. 8 '*hypatôn* mode'.

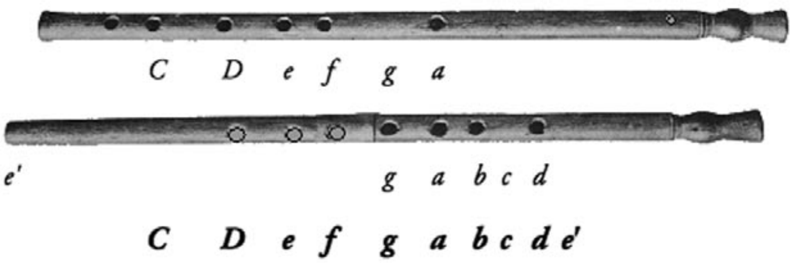

Fig. 9 'Dorian *nḗtē* mode'.

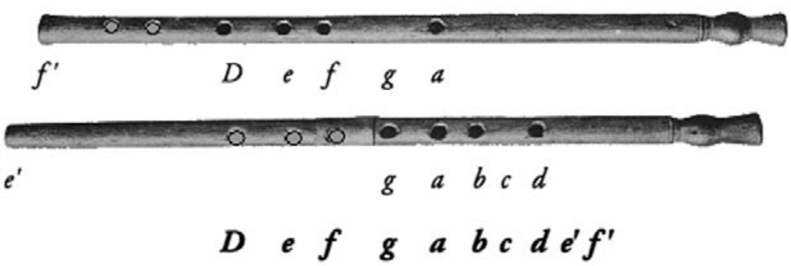

Fig. 10 '*trítē hyperbolaíōn* mode'.

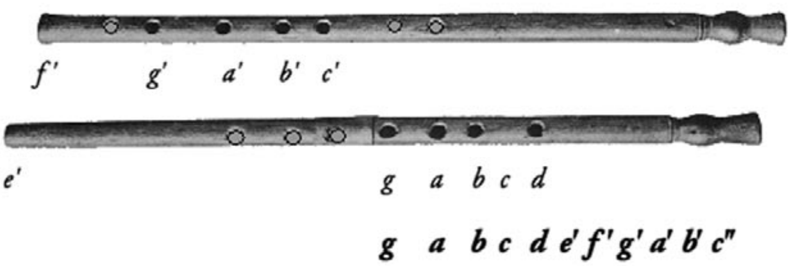

Fig. 11 Partial *syrigmós.*

In order to extend the range upwards, we remove the plugs from the highest holes of 12461, placing them on the pair of lowest holes beneath the ring of 12462 instead; the ring remains shut. At the upper end of the same pipe, however, we push back the edge of the waxen plug covering the *sýrinx* hole, so as to produce the tiniest of apertures (Fig. 9). If the remaining holes of this pipe are all covered by the finger tips, it will now overblow to *e'*, completing the tetrachord *diezeugménōn* (Track 5). In spite of the large ambitus, here a major tenth, two pitches are now shared between both pipes, suggesting modes focusing upon *G* and *A* respectively.

If an *f′* is also required, the two lowest holes of 12461 must be blocked as well, and its *sýrinx* manipulated accordingly, so that its bass note overblows easily, but not so those produced from the finger holes. The resulting gamut is once more a minor tenth (Fig. 10). Note that the melody must be transferred from one pipe to the other whenever the two highest notes appear in melodic succession (Track 6).

If the register holes are uncovered entirely, the notes produced from finger holes will also tend to the higher registers; the ensuing sound was called *syríttein*, 'whistling', in contrast to *auleîn*, 'playing the aulos', in what was apparently conceived as the 'proper' sense of the word. I give only one example, demonstrating the possibility of mixing higher and lower register between the two pipes (Fig. 11; Track 7).

I hope these pseudo-musical exercises will be felt to sufficiently corroborate the validity of the foregoing theoretical analysis in two aspects: firstly, that the two pipes that were the subject of the present investigation can indeed be played as a pair, harmonically complementing and supplementing each other; secondly, that these relatively small and inconspicuous pipes testify to a highly versatile type of instrument. With its mode switch, its additional finger holes and its simple *sýrinx* it stands halfway between more primitive types and the highly refined auloi that played in the theatre and the concert hall. Its close affinity to the Louvre aulos in certain but not all respects has led us to suppose the existence of a class of transposing instruments, built in varying pitches, whose design was based on the 'Perfect System' of Greek musical theory. I have argued previously that the origin of such instruments is to be sought in the early fourth century BC, in an environment where the aulos was still accepted as a model instrument for music theory[34]. Apart from a passage in Aristotle citing a theory that links aulos scales with a kind of cosmic harmony, the most important relevant testimony comes from the pseudo-Euclidean *Division of the Canon*. This work, written not earlier than the late fourth century BC[35], is the first extant text to construct a musical scale by dividing a vibrating string. The way it defines this string's overall length in relation to aulos-based terminology (the undivided string is called *bómbyx*, i.e., 'the entire pipe' and equated with *proslambanómenos* as the lowest note of the scale) demonstrates that the much more exact approach of string division was in fact secondary to the art of drilling finger holes at appropriate positions. This is in fact little wonder, because lyres have no frets, and instruments of the guitar family were not prominent in ancient Greece (there are hardly any references before the time in question). The *Division of the Canon* as well as Aristoxenus already presuppose the terminology of the 'Perfect System'. Consequently, this model scale was apparently established prior to the adoption of the canon; my interpretation of the Aristotle passage only supports the conclusion that the 'Perfect System' originated in the material context of aulos design. On balance, I think it is probable that the Berlin aulos stands in this tradition, reflecting many design elements that were first conceived in the late classical period.

ACKNOWLEDGEMENTS

I want to express warmest thanks to Dr. Olivia Zorn and Margret Pohl from the Berlin Egyptian Museum and to Dr. Andrzej Ćwiek from the Poznań Archaeological Museum, who allowed and helped me to study the pipes, as well as to Dr. Kurt Osterloh and Jochen Robbel of the German Bundesanstalt für Materialforschung und -prüfung, who most generously X-rayed the Berlin pipe.

34 Hagel 2005 (cf. also Hagel 2004, 384).
35 Cf. the excellent analysis in Barker 2007, 364–410.

SOURCE

Aristoxenus, *Harmonics*: Aristoxeni Elementa Harmonica, ed. R. Da Rios, Rome 1954.

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TRACKLIST

Replica of Aulos Berlin Egyptian Museum 12461/ 12462: examples of possible scales, played in circular-breathing technique and including *sýrinx*-aided overblowing. Played and recorded by the author.

Track 1 0:19 min
'Simple *G/D* mode': all finger holes open.

Track 2 0:13 min
'Simple *E/A* mode': metal ring closed; drone on *mi.*

Track 3 0:14 min
'Simple *E/A* mode': metal ring closed; drone on *la.*

Track 4 0:07 min
Figure 8: '*hypatôn* mode': metal ring and two highest holes of 12461 closed.

Track 5 0:13 min
'Dorian *nḗtē* mode': metal ring and two lowest finger holes of 12462 closed, its *sýrinx* hole slightly opened.

Track 6 0:10 min
'*trítē hyperbolaíōn* mode': as previous, but two lowest finger holes of 12461 closed, its *sýrinx* hole slightly opened.

Track 7 0:20 min
Partial *syrigmós*: both *sýringes* opened; 12462 as in previous; lowest and two highest finger holes of 12461 closed.

Fig. 12 Berlin Egyptian Museum inv. 12462, metal ring.

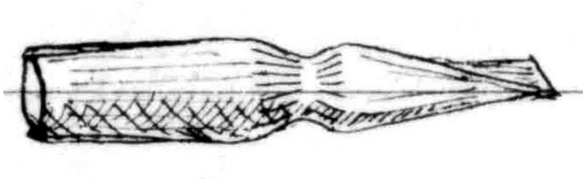

Fig. 13 Berlin Egyptian Museum inv. 12461, lost double reed: drawing in the inventory book of the Egyptian Museum, Berlin (photographed by the author).

Fig. 14 Berlin Egyptian Museum inv. 12461 (above) and 12462 (below), lower ends (montage of photographs by the author).

Fig. 15 Berlin Egyptian Museum inv. 12461 (above) and 12462 (below), upper ends (montage of photographs by the author).

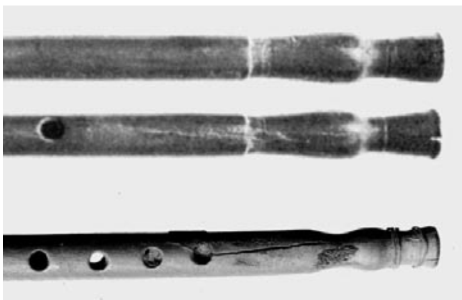

Fig. 16 Upper ends of the Louvre aulos and Berlin Egyptian Museum inv. 16401 (not to scale) (Bélis 1984, courtesy: Ägyptisches Museum Berlin).

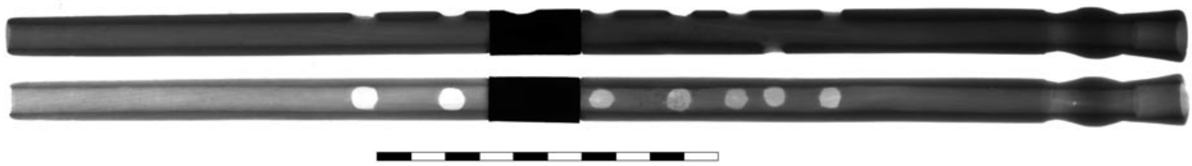

Fig. 17 Berlin Egyptian Museum inv. 12462, digital X-ray, upper image: 30 kV, 3 mA, 1 min at a distance of 1000 mm, lower image: 30 kV, 5 mA, 1 min at a distance of 1000 mm (Bundesanstalt für Materialforschung, Berlin). Note that the edges of the two parts do not quite meet inside the metal ring; in the lower image; the thumb hole side is closest to the film.

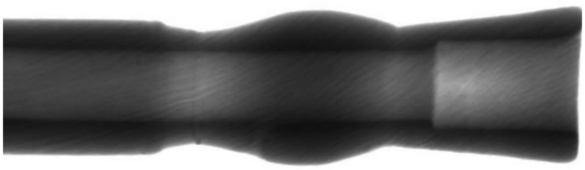

Fig. 18 Berlin Egyptian Museum inv. 12462, bulb and reed insert, small hole. Digital X-ray: 30 kV, 3 mA, 1 min at a distance of 1000 mm, object raised 130 mm above film (Bundesanstalt für Materialforschung, Berlin).

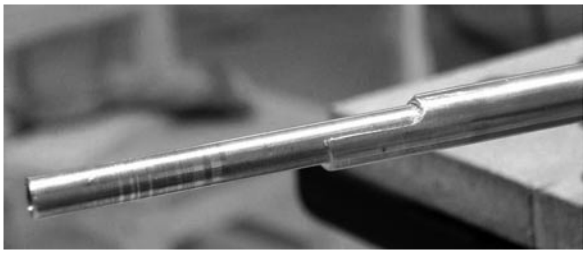

Fig. 19 Drill for reproducing the reed insert of Berlin Egyptian Museum inv. 12462 (photographed by the author).

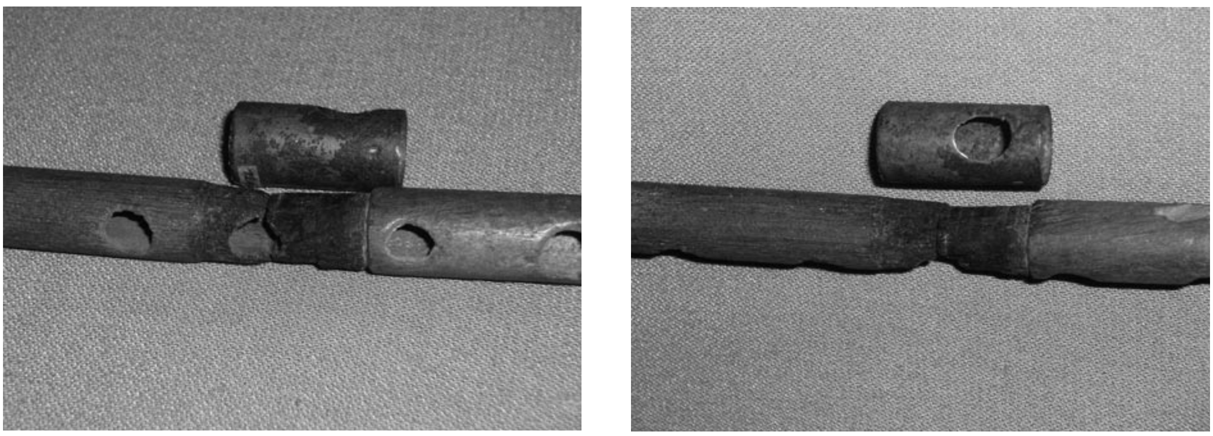

Fig. 20 The joint of Berlin Egyptian Museum inv. 12462 (photographed by the author).

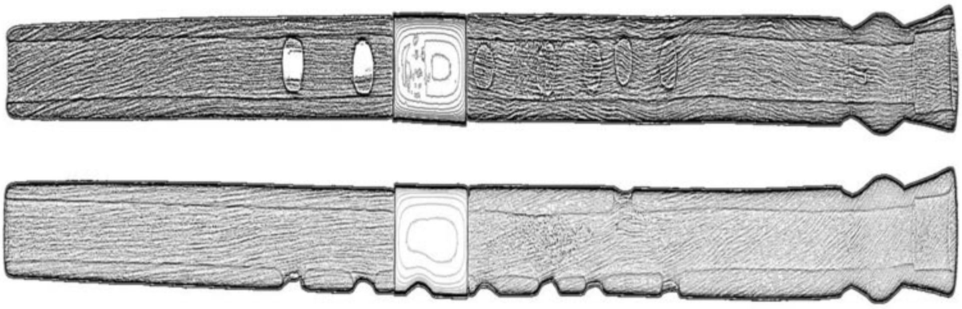

Fig. 21 Berlin Egyptian Museum inv. 12462, as figure 17, processed with Laplace filter and stretched transversally by the factor of three.

Fig. 23 The joint of Berlin Egyptian Museum inv. 12462, opened up (photographed by the author).

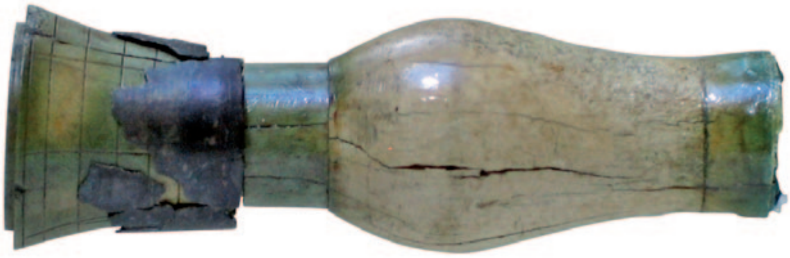

Fig. 24 Naples National Museum inv. 76892, bulb plus reed insert (photograph courtesy: Soprintendenza per i beni archeologici delle province di Napoli e Caserta).

Fig. 22 Naples National Museum inv. 76894 (photograph courtesy: Soprintendenza per i beni archeologici delle province di Napoli e Caserta).

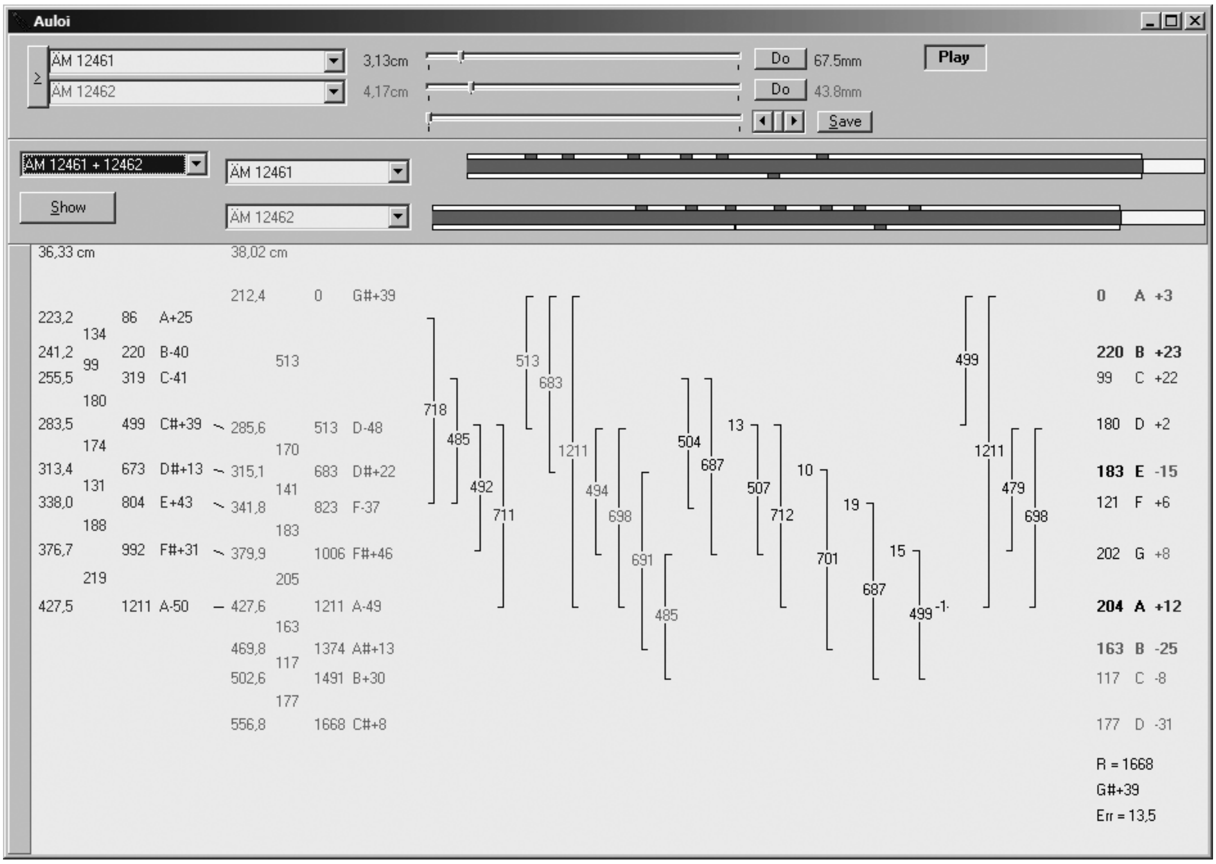

Fig. 25 Calculating the scale of Berlin Egyptian Museum inv. 12461/2.

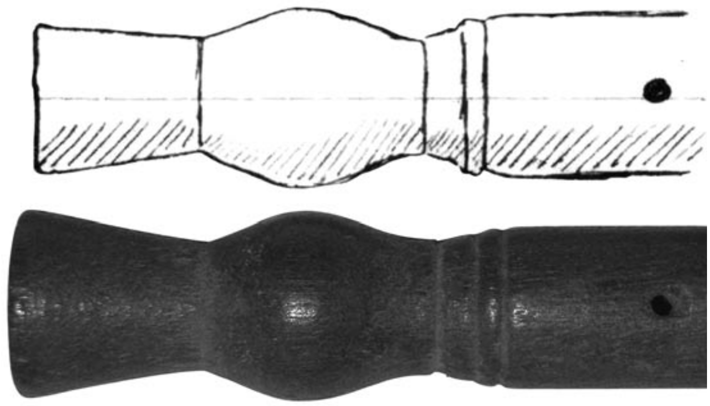

Fig. 26 Upper end of Berlin Egyptian Museum inv. 12461, Museum inventory drawing and photograph (courtesy: Egyptian Museum Berlin, photographed by the author).

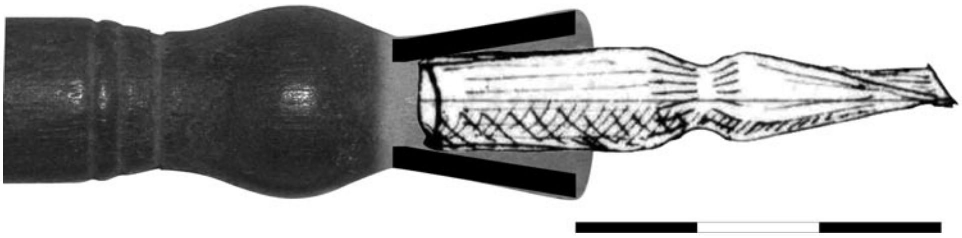

Fig. 27 Approximate scaling of the reed of Berlin Egyptian Museum inv. 12461 (montage by the author).

Fig. 28 Sections of Naples National Museum inv. 76894, with attached and traces of lost 'handles' (photograph courtesy: Soprintendenza per i beni archeologici delle province di Napoli e Caserta).

Fig. 29 Reconstructing Berlin Egyptian Museum inv. 12462: applying a layer of resin (photographed by the author).

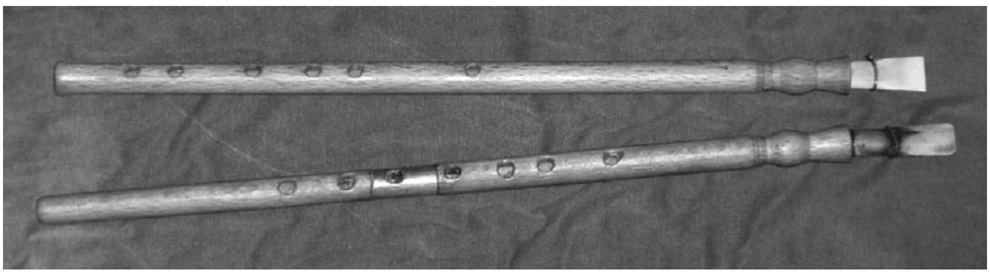

Fig. 30 The author's reconstruction of Berlin Egyptian Museum inv. 12461/12462 (photographed by the author).