DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

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JOINT FIRE RESEARCH ORGANIZATION

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## THE LEGEND OF ARCHIMEDES AND THE BURNING MIRRORS OF SYRACUSE

by

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The story that Archimedes set a Roman fleet on fire at Syracuse (c.212 B.C.) by means of burning mirrors is probably the oldest of the legends of Science. The belief still survives although there are good historical, military and scientific reasons for doubting whether Archimedes did, or indeed could have, set the fleet of Marcellus on fire.

There are several considered studies of the historical evidence[1-5]. All mention the curious silence of Polybius[6] whose histories were written not long after the battle, of Livy[7] and of Plutarch[8], although these all give detailed accounts of the part played by Archimedes in the defence of Syracuse. The earliest record of a conflagration is in Lucian[9] c.150 A.D.: he does not say that Archimedes used burning mirrors, only that Archimedes used scientific means. Galen[10], who probably wrote a few years' later, writes of something more akin to Greek Fire. Apuleius[11] is the first to associate Archimedes with a burning mirror, but he does not mention his using it to set Roman ships on fire; a detail he would hardly have omitted had he known of it.

The earliest available, unequivocal statement that Archimedes used a burning mirror to set fire to a Roman fleet is that made by Anthemius of Tralles[12] living 700 years after the event and the earliest available circumstantial accounts of this are by the Byzantines Zonaras[13] and Tzetzes[14] nearly 1400 years after the event. Although they claim to be quoting from writers now lost, the comment of Eecke[15] about the feebleness of the historical evidence seems fully justified.

The next question to be considered is whether Archimedes knew enough optics to construct a mirror with the required properties. Forbes[16] shows that the Greeks were familiar with burning mirrors and that there were arguments on how they worked. Euclid[17], Archimedes' contemporary, gives the position of the focus of a concave mirror incorrectly at the centre and not at the point half-way between the centre and the surface of the mirror. Apollonius[18], however, knew at which point ignition took place. Heath[19] argues therefore that the knowledge of a geometrical proof that some conic sections could act as burning mirrors was well known. Huxley[20], on the contrary, suggests that Anthemius was the first to prove this. If Huxley is right, it makes it unlikely that Archimedes could have

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devised such a sophisticated version as a burning-mirror in the form of a paraboloid made from flat plates (the only practical type of mirror that could have had a long enough focus).

There remains the problem of whether a burning mirror could have set the ships on fire and, if this were so, whether it would have been used. Buffon[21] showed that a burning mirror constructed from a number of plane mirrors could ignite wood at a distance of 120 feet or more. Middleton[22] has calculated that the intensity of radiation at the focus of these mirrors was about 0.43 cal $cm^{-2}$ $s^{-1}$; this is rather less than the critical value for spontaneous ignition[23]. Even assuming that the intensity were higher than that calculated by Middleton, the minimum intensity of radiation required to ignite wet wood such as in ship's timbers would be much higher[24].

Nonetheless, even if his conditions were near the threshold level, Buffon did succeed in igniting wood. It is, however, necessary not merely to ignite the wood, it must also continue to burn. Generally, flat thick specimens of wood, like ship's planks, do not continue to burn once the irradiating source has been removed (a commonplace of observation): dihedral and tetrahedral corners tested, burnt rather longer but even so the flame died out quickly on the wetter specimens[25]. Thin materials, such as papers or cloths, do continue to burn. This suggests that only thin materials on ships could be destroyed by burning mirrors; these might include the sails, although normally the Romans furled them near the shore[26] and any clothing the Romans were wearing. In such circumstances, the major source of damage would be burns to the skin which would occur at much lower intensities of radiation[27] (c.0.03 cal $cm^{-2}s^{-1}$). Furthermore, Buffon's experiments were carried out under static conditions. That is to say, the focal length could only be adjusted slowly by a large number of assistants.

Scott[28] argued that Tzetzes' description of the burning mirror was accurate and calculated that the intensity of radiation after reflection from the outer ring of mirrors on to the inner mirrors should be great enough for ignition at the focus. Further Scott pointed out that by only having a few large mirrors, the task of adjusting the focus becomes much simpler and well within the bounds of technical possibility for one or two men. Notwithstanding this, it is not merely necessary to alter the mirror's focus in order to attack different ships, that is major adjustments, the focus must be kept in the same place on the ship. The intensity of radiation could hardly be more than 1 cal $cm^{-2}$ $s^{-1}$ so that ignition under most favourable conditions would take at least 30 seconds[24]. With a moving ship - as Montucla[29] pointed out ships drift and rock even at anchor - it would have been extraordinarily difficult to keep the focal spot constant in position for 30 seconds, to less than $\frac{1}{2}^{o}$, which, with a 15 cm diameter focus, would mean that the same spot would be irradiated continuously 50 metres away. Even if ignition occurred, with a ship of, say 240 feet in length[30], it would take nearly 4 hours to ignite one side of one ship. The initial rate of flame spread would be almost as slow.

If Tzetzes[14] or Zonaras[13] are to be believed, Archimedes first allowed the ships of Marcellus to come within reach of grappling machines, then, after the ships had had to withdraw a little, he used slings to throw stones at them, and then, and only then, when they had withdrawn to a bowshot away did he use the burning mirror. At first thought, it would be more appropriate to have used the mirrors first, since normally one tries to keep the enemy as far away as possible. Against this, it perhaps might be argued that this was the necessary order because, unless the ships were in complete confusion, a bowshot or stone could have disabled the operator. Plutarch claims[8] that the Romans were terrified by Archimedes' devices - even though according to him[31] they had long been familiar with the burning glass - but if they were only a bowshot away it is unlikely that every man would be so paralysed that he would be unable to use his bow to attack Archimedes (and any operators). And it is still more difficult to believe that all the ships (for Zonaras leaves none to survive) would be within the range and operating angle of the mirror and that none attempted to escape.

If then, as I suggest, the feat was impossible, and as Montuola[29] said much less feasible than throwing the predecessor of Greek Fire, how did the story originate?

Now, none of the surviving records of Archimedes' contemporaries or near contemporaries mention a fire in a Roman fleet off Syracuse, but Diodorus[32] (whom Tzetzes claims he is summarising) possibly quoting Thucydides[33], does give an account of a fire in a fleet off Syracuse. It is a Greek fleet, however, and fireships were used unsuccessfully and the battle, which took place 200 years earlier, was between the Athenians and the Syracusans in the Pelopennesian war (c.400 B.C.). The origin of the 'fire' story in Galen and Lucian is perhaps due to the confusion of two sea battles off the same town; once the later date was used, it was natural to link Archimedes' operations with the cause of the fire.

How the burning mirror version arose is more difficult to explain, other than by gossip. It may be that the reference to Archimedes in Lucian was extended to include another passage[34]:

"It would take no little time to sing his (i.e. Hippias')
praises in the doctrine of rays, refractions and mirrors."

This, together with the knowledge or belief that Archimedes kindled fires by burning mirrors would complete the story.

References

(1) Heiberg, J. L. Quaestiones Archimedeae, Leipzig, 1879 p.39.

(2) Eecke, Paul van der. Archimedes, Paris, 1921. Introduction p.XIX-XXII. 2nd Edn. 2 vol, Leige, 1960.

(3) Heath, T. L. Works of Archimedes, Cambridge, 1927 p.XXVII.

(4) Dijksterhuis, E. J. Archimedes, Copenhagen, 1956, p.28.

(5) Burger, D. Faraday, 17, 1947/8, p.1-5.

(6) Polybius, Histories, London, 1927, p.451-3.

(7) Titus Livius, trans. Foster B.O., London, 1952. Vol.6, p.283-7, (214 B.C.) (siege), (212 B.C.) 461 (death).

(8) Plutarch's Lives, trans. Langthorne, W. London, 1886, p.49.

(9) Lucian of Samosata, Hippias, Works, Vol. I, London, 1913, p.37.

(10) Galen, de temperamentis, 3.2.

I have found no modern edition of this work in English.

(11) Butler, H. E. Apologia of Apuleius of Madaura, Oxford, 1909, p.42.

(12) Huxley, G. L. Anthemius of Tralles, Cambridge, Massachusetts, 1959, p.12.

(13) Carey's translation, Dio's Roman History, London 1914. Vol.2, p.171 ff.

Zonaras 9.4 is given as

"At last in an incredible manner he burned up the whole Roman fleet. For by tilting a kind of mirror toward the sun he concentrated the sun's beam upon it; and owing to thickness and smoothness of the mirror he ignited the air from the beam and kindled a great flame, the whole of which he directed upon the ships that lay at anchor in the path of the fire until he consumed them all.

(14) Carey, loc. cit. p.171 f.

Tzetzes Chil. 2. 109-23 is given as

"When Marcellus withdrew them a bow shot thence (after having moved them from the wall by engines and then by hurling stones), the old man constructed a kind of hexagonal mirror, and at an interval proportionate to the size of the mirror, he set similar small mirrors with four edges moving by links and by a kind of hinge, and made the glass the centre of the sun's beams - its noontide beams, whether in summer or in the dead of winter. So after that, when the beams were reflected into this, a terrible kindling of flame arose upon the ships, and he reduced them to ashes a bow shot off.

(15) Eecke, loc. cit. P. XIX.

(16) Forbes, R. J. Studies in Ancient Technology, Leyden 1957-8, Vol.V., VI.

(17) Eecke, Paul van der. Euclid's Optica and Catoptrica, Paris, 1938, p.XXXI.

(18) Heath, T. L. The fragment of Anthemises on burning mirrors and the Fragmentum mathematicum bobiense, Bibliotechna Mathematica, t 7, 225-233, 1907, p.232.
"There can be no doubt that the fact that the ellipse has the property of reflecting all rays through one focus was known to Apollonius".

(19) Heath, loc. cit. p.230.

(20) Huxley, loc. cit. p.28-9.

(21) Middleton, W. E. Knowles, Archimedes, Kircher, Buffon and Burning Mirrors, ISIS, 52, (4) 170, 1961, p.543-553.

(22) ibid, p.542.

(23) Lawson, D. I., and Simms, D. L. The ignition of wood by radiation, Brit. J. appl. Phys., 1952, 3 (9) 288-92.

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(26) Letherbridge, T. C. On shipbuilding, History of Technology, Ed Singer, Holmyard, et al. Vol.II, Oxford, 1956, p.570.

(27) Buettner, K. Effects of heat and cold on human skin. Part II J. appl. Physics, 1951, 3 (12) 703-13.

(28) Scott, J. Trans. Roy. Soc. Edin. XXV, 1869, p.123-149.

(29) Montucla, J. E. Histoire des Mathematiques, Paris, (2nd Edition, ed. Llande) 4 vol, 1799-1802. Book IV. p.247.

(30) Letherbridge, loc. cit. p.573. "He suggests that Mark Antony's cataphracts at Actuum might be comparable in size with British ships of the line of 1852".

(31) Plutarch, life of Numa, quoted by Forbes, loc. cit. p.184.

(32) Diodorus Siculus, trans. Oldfather, C.H., London, 1933, Vol. p.161.

(33) Thucydides, trans. Warner R., London, 1956, p.456.

(34) Lucian, loc. cit. p.38.