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CHAPTER 10

Aesthetics and the Foundations of Science: Insights from Indian Metallurgical Traditions*

Sharada Srinivasan

INTRODUCTION

This essay attempts to explore insights into the foundations of science from a study of Indian metallurgical traditions, especially concerning the role of aesthetics versus functionality in scientific innovation. This essay does not restrict itself to questions related to the foundations of Indian metallurgical traditions *per se*, but tries to explore the broader picture of what Indian metallurgical traditions

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may tell us about the foundational aspects of science at large. These aspects range from diverse issues such as the 'Needham paradox' in the Indian context—whereby certain eastern transfers of technology from India to the West spurred eighteenth century innovations in Western science despite stagnation in India itself (for e.g. wootz steel and isolation of zinc)—to the possible relevance of Indian metallurgical heritage for modern science as exemplified by a world-famous neuroscientist's attempt to explain a new discipline of 'neuro-aesthetics': through studies on a tenth century Chola bronze goddess.[1]

To argue that aesthetics has played a role in laying the foundations of science, one need look no further than to the extraordinary life-story of that scientist-aesthetician *par excellence*, Indian Nobel Laureate Sir C.V. Raman (1888–1970) born in Thiruvanaikkaval in Tamil Nadu.[2] Himself trained as a Carnatic violinist, his phenomenal work on light and acoustics, which was especially remarkable given the Indian circumstances at the time, was inspired by such things of beauty as the music of the traditional stringed veena (which his wife played), his brilliant perception of colours ranging from the Mediterranean blue to the plumage of the peacock, from solar to lunar coronae and from the peerless pearl to the diamond. One could claim that Raman's special genius also drew partly from the same wellspring of the Indian tradition, which threw up an all-time great manifestation of a synthesis between art and science, i.e. the Natarāja bronze from Tamil Nadu. Indeed, it is remarkable that such an Indian icon was formulated at least half a millennium before the time of Leonardo Da Vinci, who famously integrated science and art as 'the quintessential Renaissance man' in the words of material scientist S. Ranganathan, editor of an issue of *Resonance* devoted to metallurgist-art connoisseur Cyril Stanley Smith.[3]

An interesting aspect that this paper touches upon is the paradox that aesthetics rather than functionality seems to have been the motivating force behind innovations in several instances in the pre-modern period. A prime example is the contrast between the highly functional, and in one sense, scientifically efficient and egalitarian use of metal and resources in the Harappan period, and the monumental, even 'wasteful' lavishness of ritually and aesthetically driven elitist artefacts from ancient Egypt, Mesopotamia or China; which on the other hand demonstrate far greater vigour in terms of innovations in materials science. However, it is also pointed out that the Harappans seemed to have been much more pre-occupied with and adept at working on the miniature scale as evidenced by crafts in lapidary, work in steatite, etc., producing for the first time a range of specialized drilling tools. Such a feel for the miniature is not out of place in the context of the scientific frontier of the future: nanotechnology.

This essay mainly discusses those Indian metallurgical contributions that seem fairly distinctive to the Indian subcontinent and thus merit some exploration into the local factors behind such innovations. In that sense this essay dwells mainly on traditions falling outside the ambit of medieval Islamic influence; which would have entailed exploring diverse geographical and literary sources outside the scope of this essay. Thus the essay mainly focuses on what may be described as being of Hindu/

Buddhist/Jain/indigenous inspiration, which perhaps presents a more self-contained system for study. Two such emphatic Indian contributions to the foundations of science are the invention of zinc smelting and high-carbon steel. For both, there is some preliminary evidence of development by the latter first millennium BCE while these technologies developed on a semi-industrial scale by the medieval period at Zawar in northwestern India in the first case and at numerous sites in the southern India in the case of the latter. In both cases, although these technologies deserve to be credited to the genius of the Hindu/Buddhist/indigenous Indian milieu, their zenith of artistry was reached through syncretism with Islamic art and technology, as seen in the high-zinc damascened Bidriware and the patterned Damascus blades.

The most famous emblem of Indian proficiency in metallurgy is the Delhi iron pillar (c. 400 CE), found to be highly corrosion resistant, which is also the earliest surviving massive iron forging in the world. Pioneering studies by R. Balasubramanium[4] have shown that its corrosion resistance was due to the phosphorus content. As far as this paper is concerned, however, it restricts itself to certain metallurgical traditions that have a bearing on arguments related to foundations of science discussed here and/or which the author has had occasion to study, particularly in southern India, although this is by no means an exhaustive list. These include the making of the high-carbon wootz steel, known as *ukku,* in parts of southern India, the earliest extraction of metallic zinc in the world with eleventh century evidence from Zawar in Rajasthan, the early development and specialized use of binary wrought and quenched high-tin bronze alloys to make vessels as seen in peninsular megaliths, especially Adichanallur and Nilgiris in Tamil Nadu, and delta high-tin bronze mirrors from Kerala that came to light with the author's investigations, the making of fine solid cast bronzes in medieval Tamil Nadu and the use of flexible spring steel blades in the Kalaripayattu martial tradition of Kerala.

Quite apart from functional aspects that explain developments in metallurgy such as the availability of ores and choice of alloys, it is also argued that certain distinctive innovations may have been driven to an extent by aesthetic, philosophical or cultural factors. Notions of inter-connectedness between sculpture, painting, dance, music and arts are found in the fifth century Sanskrit treatise of the *Viṣṇudharmottara Purāṇa.* Such sensibilities permeated a range of traditional Indian artistic outcomes from the synthesis of temple architecture, sculpture and dance, to the *rāgamālā* paintings bringing together painting and music. Consequently, it is not irrelevant to look at how such ideas of interconnectedness also impinged upon the emergence or development of technologies.

An analogous approach from the Western anthropological tradition which may be useful in understanding the way Indian innovations may have been arrived at through a synergy between diverse and inter-connected interactions, may be that of dialectic holism. A dialectical approach to the human condition emphasizes the importance of dialectical relationships, whereby a network of cause and effect affect each other and has ramifications for the inter-relationship between parts that make up the whole.[5] Dialectic holism is based on the view that human beings are open systems, whereby the mind and body, individuals and society, and individuals and the environment interpenetrate one another and where the importance of human agency is recognized.[6]

Thus the essay seeks to explore the interplay between functional and cultural imperatives through which one may explain the preferential emergence of certain technologies. Some interesting perspectives are provided in the case of the extraction of metallic zinc by downward distillation, which Indians can claim credit for over the rest of the world. Zinc was also often referred to as *rasa* in Sanskrit alchemical texts, for which there is a striking analogy with the concept of *rasa* in Hindu or Indian aesthetic or dramaturgical theory, which can be understood as something of a sublime, distilled essence of an aesthetic or spiritual experience. As another example, it may be speculated that the early and highly elegant use of wrought and quenched high-tin bronze alloys in peninsular Indian megaliths might be linked to an ancient predilection for performance and musical materials going back to Neolithic southern India. Thus the essay seeks to explore whether and how artistic, philosophical, ritual or performance art-related aspects or impulses dovetail into or shape 'technological outcomes' such as a metal artefact. As indicated here, the insights from surviving craft traditions can also be crucial to such an understanding.

If one were to describe certain Indian scientific discoveries such as zinc smelting as a by-product of peculiarly Hindu/Buddhist/Jaina aesthetic or philosophical sensibilities, it is also interesting that there is little evidence that this zinc or brass was being used towards making mechanical or scientific instrumentation, apart from ritual, decorative or utilitarian purposes in earlier periods. In fact, good evidence for the use of such brass for the advancement of scientific knowledge is really only seen from the time of the high zinc brass astrolabes of sixteenth century Islamic Mughal India from Lahore, Pakistan, where the high aesthetic sensibilities and refined craftsmanship of the period undoubtedly contributed to the making of high-precision instruments. At the same time, this essay points to at least one fine example of the use of metals in instrumentation related to Hindu ritual and astronomy, of a clepsydra or sinking water clock (*ghaṭi-yantra*), from Kerala, a region known to have had a high tradition of astronomy and mathematics. This water clock appears to be extremely skilfully made of finely wrought and quenched high-tin bronze. Here, too there is evidence that this technical skill draws from an ancient tradition of high aesthetics and technical finesse in working high-tin bronzes going back to the south Indian megalithic period, with the finds from the Nilgiri megaliths and Adichanallur burials representing some of the most extensively and finely wrought and elegant examples of quenched high-tin beta bronzes (23 per cent tin) found anywhere. In general, though, it may be said that the use of metals for mechanical gadgetry to improve quality of life seems to have been less of a concern in Indian antiquity than in Europe, China or the Islamic world.

Some intriguing fundamental issues concerning the scope and limitations of Indian traditional knowledge systems are also touched upon. Clearly, India did enjoy primacy over Europe and elsewhere in some remarkable empirical discoveries, such as the making of high-carbon wootz steel (which continued well into the seventeenth and eighteenth centuries) and zinc smelting, which were also successfully replicated on a near industrial scale. In the case of zinc smelting at least, there is evidence of fairly meticulous documentation of the processes in Sanskrit iatro-chemical treatises. Despite all this, the hard science of understanding, documenting and then most importantly applying the underlying principles towards generating newer innovations had to await the European interventions of the colonial period, specifically the Age of Enlightenment. This was a period when significant inter-disciplinary interactions between humanistic and scientific activity thrived. This in a sense reinforces the case that, at least in the pre-industrial era, a highly charged cultural-aesthetic milieu often had a positive bearing on scientific innovation. From the perspective of history of science, an attempt is made here to retrieve some of the 'inventions' patented in the eighteenth-nineteenth century that were inspired by eastern or Indian sciences. Whereas European science, as in the case of arts, was marked by individualism where names, credit, individual patents and signed artworks were the order of the day, Indian crafts or knowledge systems seemed to have placed the product above the individual, whereby the practictioner remained largely anonymous. There are a few exceptions to the anonymity, such as Nāgārjuna, who is thought to have lived around 400 CE in southern India; it is interesting in connection with some references to zinc metal in Nāgārjuna's writings that this paper reports a find of zinc metal in southern India during this period, which is one of the earliest such finds in the world.

Overall, it is hard to escape the impression that the ritual/aesthetic/philosophical domains dominated the context in which metals were traditionally used in India even when scientific ramifications are involved, as in the case of the Aranmula mirror of delta bronze (32.6 per cent tin bronze) which provides a unique pre-modern example of the optimization of the delta intermetallic phase compound of bronze to get an ideal mirror effect. This also seems to be the case with the Naṭarāja bronze of the dancing Hindu God Śiva, whereby studies reported here suggest a close match of the star positions of the constellation Orion with the iconography of a Pallava bronze (c. 800 CE), which could be proof of astonishing astronomical skills. Taken together with some mystical poems by Tamil saints, it appears that nascent ideas of cosmic creation and destruction did underpin the Naṭarāja icon;[7] so that the suggestion of renowned astronomer Carl Sagan that the Chola Naṭarāja bronze imagery represented 'a premonition of modern astronomical ideas' is not overstated.[8] This millennium old image has provided intriguing metaphors that help to relate to the implications of modern physics. Indeed, Capra compared the dance of subatomic particles to Śiva's dance;[9] while the worship of Naṭarāja at Chidambaram as both formless space (*ākāśa lingam*) and the iconic dancing image is evocative of concepts like wave-particle duality.[10] It is almost as if the real accomplishment or relevance of these nascent quasi-scientific ideas, which emerged out of a rich poetic, aesthetic and ritualistic milieu as exemplified by the hymns of Saivite saints and the fine processional bronzes, is not to be found in their own time but a millennium later, in the present. Thus, one may controversially argue that such post-modernist, aesthetically driven, shifting interpretations of Hindu thought have contributed to a certain *Weltanschauung* that may in some ways be better reconciled to take on the philosophical challenges of modern science than world views that may be overtly tied to historical events: which may even explain to some extent the recent leapfrogging seen in parts of India from a post-colonial subsistence-type developing economy to something approaching a 'high-tech, knowledge-driven' one.

SCIENTIFIC INNOVATION, HUMANITIES AND AESTHETICS: SOME CONSIDERATIONS

Eminent chemist Alan Mackay[11] in a thought provoking essay 'Foundations of Chemistry' cautions against the pitfalls of post-modernism, 'where all systems of analysing the world may be regarded as equally valid and where the material basis of the world is hardly distinguished from its verbal representation'; nevertheless there are some interesting insights to be gained through the interpolation of the domain of the philosophers and humanists into that of science.

Indeed, according to Mackay the foundations of the great scientific revolutions of Europe's Age of Enlightenment were laid through the 'think–tank' like, broad-based intellectual climate of the eighteenth century which encouraged dialectic relationships, with interactions ranging from atheists to clerics.[12] To quote him,

> A most important example was the *Coterie Holbachique*, the dining group of the Enlightenment. Baron d' Holbach provided the immeasurably valuable subsidy to science and learning by giving dinner in his house in Paris for twenty people twice a week for thirty years. The leading figure was Denis Diderot (1713–1784) and several members contributed to the Encyclopaedia but many other significant people attended, incl~~uding foreign visitors such~~ as Benjamin Franklin and the intellectual climate of the eighteenth century was formed through the uninhibited discussions to and fro in an informal dialectic which took place in freedom and privacy. Although several figures were atheists several clerics attended. There have been many other such dining groups which sought by discussion to form a common intellectual atmosphere but none so important.

The above is one example of how scientific inspiration in the pre-industrial era derived from a wide-ranging milieu encompassing the humanities as well as the sciences.

In fact, it is extraordinary that archaeological research has validated the radical notion that it was aesthetics and not economics or functionality that could have played a driving role in the foundations of metallurgy and hence science as indicated in Killick.[13] This idea was mooted by Cyril Stanley Smith in case of the development of pyrotechnology in the pre-history of the Near East, that crucible of the world, and was later validated through research on the origins of metallurgy in both the Old World and the New World. It is useful to cite the insightful comments of David Killick in encapsulating these epochal developments in theoretical archaeology. Killick describes as one of the founding fathers of modern archaeometallurgy, Cyril Stanley Smith (1903–92), who was 'an eminent solid state physicist who developed in mid-career a passionate interest in the history of metallurgy.' Killick mentions that Smith drew on his analytical experience of applying material science to the study of scientific and prehistoric artefacts to propose a truly radical theory of the invention of pyrotechnologies. He noted that the earliest examples of these artificial materials tended to be beads, figurines, pendants and other ornaments rather than functional tools or weapons. Smith argued that the origins of pyrotechnology lay more in aesthetics than in economics. Subsequent research in the Old World on the origins of metallurgy, lime plaster, ceramics and glass has largely confirmed his theory.[14]

Killick also cites the work of Binford to say that 'in the New World, as in the Old, the earliest known metal objects were made for displays of status as grave goods, not for hunting, agriculture or warfare.' Binford was one of the early proponents of post-processualist archaeology, which takes the view that the exploration of aspects such as symbolism, meaning and agency have a critical role to play in archaeological interpretation over and above a structuralist/processualist approach based on data collection and scientific evidence.

There are also clear instances of aesthetic impulses leading the way to technological innovation: in the period leading up to the Industrial Revolution. As pointed out by Smith, it was the European attempts in the eighteenth century to duplicate the beautiful and much sought after Chinese porcelains that inspired the development of high-temperature techniques and analytical procedures and work on silicates and other minerals and clays.[15] As Smith points out,

> A materials-oriented view of history may overemphasize the association of technology with art, yet it was precisely the artists' search for a continued diversity of materials that give this branch of technology its early start and continued liveliness despite an inner complexity which precluded scientific scrutiny until very recently ... The antecedents of today's flourishing solid-state physics lie in the decorative arts.[16]

We have already pointed to the profound inspiration that the iconic Indian physicist C.V. Raman, who was awarded the Nobel Prize in 1930 for his work on light scattering and the Raman effect, derived from a range of aesthetic experiences. A concrete example of the impact of art on the scientific enterprise is put forth in the elegant book *Beyond Vision* by the late Jon Darius, then Curator, Astronomy, Science Museum, London, himself accomplished as both an astronomer and musicologist, which points out that scientific photography, upon which so many crucial scientific experiments have hinged, 'arose not so much in the chemical laboratory as in the artist's studio.'[17]

Another example of the enmeshing of scientific creativity with near mystical inspirations or aesthetic responses is suggested in an epoch-making scientific photograph related to wave-particle duality, also elucidated in *Beyond Vision.* This is in the context of one of the great debates of twentieth century physics: over the fundamental nature of radiation and matter and whether light could really be described as particles and matter. Darius describes George Thomson's experiments wherein electrons were fired through celluloid film and gold foils that resulted in patterns being formed on photographic plates of concentric rings, with the larger rings being associated with lower energies.[18] Thomson, who was, interestingly, a professor of natural philosophy at the University of Aberdeen, described the photographs, rather poetically, as 'recalling in appearance the haloes formed by mist around the sun.' As pointed out by Darius, 'the dualism between waves and particles had become inescapable, and these epochal experiments earned C. J. Davisson and G. P. Thomson the Nobel Prize for Physics in 1937.'[19] This account also interestingly captures the paradox of duality and even complementarity between science and aesthetics, whereby the dry practice of science results in its own way in the most aesthetic of outcomes. Neuroscientist V. S. Ramachandran points out that science deals with universal principles, whereas art is the ultimate celebration of human individuality and originality.[20] In so far as artistic activity or aesthetic pursuits keep alive the streak of human originality or creativity, it can be seen to inspire scientific innovation as well.

As such, although scientific activity as practiced in the modern context may seem acultural and universal, it is certainly relevant in terms of the history of science to explore how the corresponding cultural milieu within which scientific innovations arose could have shaped them. In the Indian context, this idea was most radically and eloquently articulated and boldly experimented with not by a historian of science but by a practising bio-technologist working on technologies for rural development, late C.V. Seshadri. Viswanathan[21] and Prasad[22] described him as an extraordinary and gifted visionary whose ideas set out to shake up conventional thinking and received wisdom on a range of issues, including even those as fundamental as the law of thermodynamics and the concept of time. Seshadri took the view that 'we recognize that all human constructs are anthropomorphic ... many concepts that are accepted as absolutely self-evident once stated of arising out of a "scientific method" are really based on very deep-seated cultural roots that need not necessarily be universal...'[23] This essay thus takes up on this challenge to explore whether certain Indian scientific innovations arose out of predominantly Indian cultural pre-occupations, as elaborated further especially in the case of zinc.

METALLURGY AND FOUNDATIONS OF SCIENCE: INSIGHTS FROM PREHISTORY AND PROTOHISTORY

The foundations of science may owe much to the earliest metallurgists of pre-history, who were probably the first experimentalists. To quote Trivedi, 'some historians believe that the discovery of converting a stone-like material (the ores) into metal was the most significant step in the history of technology. While the extraction of copper from its ores was important, the most important result was that this discovery led to experimentation, forming the basis of modern science and technology.'[24]

To summarize some of these early steps to laying the foundations of not just metallurgy but of experimental science and technology, the earliest discovery and use of metals was of metal found in their elemental states as native copper, gold and silver in vein deposits or alluvial deposits. This took place in the Near East around 8000 BCE, where it was discovered that these softer metals could be hammered and worked to shape. Thereafter it seems that around 4000 BCE it was found that when a metal was hardened from working, it could be softened or annealed when heated in fire. This was an important milestone in the history of not just metallurgy but also materials development and processing since it was the first heat treatment of metals. However, it was not for another 2,000 years that the next giant leap in the history of technology took place, i.e. the discovery of the smelting of copper ores to copper, of the separation of metal from ore by heating. Some of the best early evidence for copper smelting comes from the Timna Valley in Israel around 5000 BCE. As pointed out by Trivedi, 'the discovery of smelting was a very significant step forward in our manipulation of nature since it enabled the extraction of vast amounts of metal which could subsequently be shaped into weapons and agricultural tools.'[25]

No doubt, such early discoveries were driven by functional imperatives of the need for tools and were often made accidentally. Nevertheless, the example of the discovery of copper smelting itself may bear out the idea being explored in this paper that aesthetic imperatives had a significant role to play in scientific innovation. It is believed that copper smelting may have been an accidental discovery made when brightly coloured copper oxide ores such as green malachite and blue azurite were selected and used as constituents to make faiences or glazes for pottery. When higher temperatures prevailed, these ores would have been reduced to copper metal. Already in pre-dynastic Egypt (c. 5000–3200 BCE) the potters had learnt the art of finely glazing and decorating pottery.

When one explores this question of functional versus aesthetic imperatives in early developments in scientific innovation, some interesting aspects come to light. It seems that when we consider the first and most evolved complex societies, i.e., the river valley civilizations of Egypt, Mesopotamia and the Indus Valley, we are presented with some interesting paradoxes. On the one hand it is the Indus Valley civilization that seems the most driven by a certain minimalistic ~~functionalism, utilitarianism and~~ even egalitarianism, and thus by these indices probably ranks as the most scientific or efficient in the modern sense. However, paradoxically, it is found to be wanting considerably in terms of the great profusion of spectacular artistic riches, luxury artefacts and monumental architecture reflecting the tremendous explosion of more advanced materials science and technology especially in ancient Egypt and also Mesopotamia, which by comparison seem to be more pre-occupied with the bizarre and the irrational, with fantastical beliefs and funerary cults. It is worth citing Schultz and Lavenda in this context:

> The evolution of complex societies seems inevitably connected with a phenomenal explosion of architectural and artistic creativity. Although anthropologists admire the material achievements of these ancient societies, many are struck by the 'wasteful' expenditure of resources by a tiny ruling elite. Why, for example, did virtually every original complex society build monumental architecture? Why did they not invest their increasing technological and organizational power in less elaborate projects that may have benefited the ordinary members of society? Why were the masterpieces of pottery, metallurgy, and weaving often hoarded and buried in tombs of dead rulers instead of being more widely available? These 'excesses' apparently did not develop in the early Harappan civilization of the Indus

> Valley, but they are so widespread elsewhere that the questions remain important.'[26]

In a similar vein, D. P. Agarwal in a comprehensive book on Indian archaeometallury makes the interesting observation that, whereas monumentality and individuality is writ large in early Chinese ritual vessels and statues, the Harappan metal tradition was very utilitarian with not much copper having been wasted on mere ritual or status symbols.[27]

Before returning to the above issues, it would be pertinent to touch upon some features and accomplishments of the Indus Valley Civilization. Spanning a vast area from parts of Pakistan to western and northwestern India, it was geographically more extensive than contemporary early civilizations with the most advanced urban town planning. What is remarkable over such a large area is the uniformity and standardization (again, a scientific idea) in the material culture as reflected in the town planning, brickwork, building, construction, pottery, system of seals, weights, measures, script, beadwork and metallurgy, indicating efficient channels of communications and trade networks. A high civic sense and the use of science and technology for improving the quality of everyday life is in evidence in the well-ventilated streets, well-developed systems of drainage and soak pits. At Dholavira, the site made of uniform limestone slabs rather than bricks, a remarkable system of rock-cut reservoirs and wells is found to serve the water needs of the populace. There is also evidence for instrumentation of various types apart from cubical weights of chalcedony, black stone, etc. Kenoyer points out that complete sets of smaller weights were found even at rural Indus Valley settlements, apart from major trading centres.[28] According to Iwata, skilled systems of Indus Valley measurements include finds of linear measures of shell and ivory from Mohenjodaro in Pakistan and Lothal ~~in Gujarat, India, some graduated even to one~~ hundredth and one four hundredth of a unit (67.6 mm) and one of bronze and copper balances with bronze beam found at Mohenjodaro.[29] Lead balls described as 'plumb bobs' have been found at Mohenjodaro, Dholavira and Saran, which may be linked to the linearity of construction. At the site of Dholavira, the author also saw circular patterns on shell debitage indicating the use of a compass, as well as an intriguing well-made coiled artefact in shell, described by the Archaeological Society of India as performing some kind of role of a compass/ruler.

The questions of why the Harappan civilization is an exception to the general 'decadent excesses' of most complex societies is an interesting one, which this essay does not fully attempt to tackle. However, the pragmatism reflected by this civilization may have been partly due to the fact that several of the sites seem to have been outposts for trade and craftsmanship. In particular, lapidary work seems to have been one of the major pre-occupations, and there is good evidence for etched carnelian and other Indus beads being traded to Mesopotamia and Oman. As noted by the author on visits to the Harappan site of Dholavira, Kutch, Gujarat, practically every living quarter in the middle town and lower town areas seemed to be littered with debitage from lapidary or shell working with rocks with grooves cut in for polishing beads. So much, so that one could visualize them as a highly industrious people whose lives revolved around such craft activities, in fact, perhaps not unlike a village in Kutch where even in recent times women can be seen deeply absorbed in their characteristic embroidery work.

Coming to metallurgy, gold and copper were used since Neolithic times in the Merhgarh area of Baluchistan in Pakistan (c. 6000 BCE). Numerous fine gold artefacts were uncovered from Mohenjodaro with examples such as diadems and a belt with intricate fish motifs (National Museum, New Delhi). Numerous Harappan gold artefacts were uncovered a few years back from a hoard in the village of Mandi in Uttar Pradesh, most of which was unfortunately looted by the locals. An abundance of Harappan silver artefacts is reported from the site of Kunal, in northwestern India.[30] The copper-bronze repertoire (with the exception of a few figurines such as of dancing girls and bulls, and ornaments like copper beads and spacers) is rather starkly utilitarian, ranging from pots, pans, razors, cobbler's tools, hairpins, sickles, blades, arrow-heads, axes, fish-hooks, chisels, spearheads, arrow-heads, straight and circular saws, mid-ribbed daggers and eye needles. Agarwal points out that the world of instrumentation owes to the Harappans the needles with eyes on the pointed end, true saws, circular saws and drills.[31] It is interesting that the Harappan finds show a distinct lack of weapons of war.[32] Kenoyer points to tentative evidence of matri-local burials suggestive of a powerful role for women in Harappan society.[33] Generally, the Harappans seem to have known a peaceful existence when contrasted, for example, with the dramatic depictions of warfare found on coeval Assyrian reliefs in the British Museum.

While there may be nothing in the Indus material culture to rival spectacular West Asian finds epitomized by the large bulls of arsenical copper from Mesopotamia, with its silvery coat due to arsenical enrichment, or the golden inlayed mask of Tutenkhamen from Egypt, or the ritual Anyang vessels of China (c. 1600 BCE), the remarkable feature of the Harappan civilizati~~on seems to have been the scale of~~ miniaturization at which its craftsmen were able to work, almost as if they were a terribly near-sighted race. This is seen in its tiny, but exquisite figurines such as the sandstone torso and famous bronze dancing girl from Mohenjodaro and in the finely carved steatite seals. Most especially this is reflected in its mind-boggling bead industry. The author scrutinized finds from Dholavira that consisted of several really tiny beads some no more than a millimeter or two, of perfect spheres, circlets, cylinders and other geometrical shapes; and pendants of gold, copper, steatite, fired stones such as etched carnelian, agate, quartz, chalcedony, jasper, turquoise, lapis, faience, shell and terracotta, with the stone beads having been pierced with drills made of the hard stone ernestite.

Indeed, the great reputation that India has enjoyed through historical periods for its traditional crafts may be traced back to Indus times, according to well-known archaeologist Jean-Francois Jarrige.[34] He states that,

> beginning with craft activities we know that India, across the historical periods, enjoyed a great reputation for the making of ornaments, of every kind of bead, of faiences, of enameled objects, of ornaments in shell, ivory and luxury textiles ... Sargon of Agade around 2300 BC considered the goods from 'Meluhha', 'Magan' and 'Dilmun' so precious that the boats shipping

> them were meant to sail the Euphrates up to Akkad, without being unloaded, like the rest of the boats, in the port of Ur...[35]

At least Meluhha has often been identified with the Indus region and numerous fine etched carnelian beads of Indus origin have been found as far away as Oman. Agrawal also cites the work of researchers on Indus craft traditions such as Vidale, who made the point that the Indus craftspeople were a fundamental component leading up the Indus civilization process and its evolution.

Going back to its early roots in the Harappan milieu, the distinctive nature of South Asian culture owes itself to the way numerous communities have interacted such that they retained their identity and yet remained inter-connected, as suggested by Allchin and Allchin.[36] To cite them,

> the character of South Asian culture as a whole is as distinct as that of Europe, for example, or China. One of the distinctive features of South Asian culture in historic and recent times is the way in which it has encapsulated communities at many different cultural and technological levels, allowing them, to a large extent, to retain their identity and establish intercommunity relationships. Early Indian literature makes it clear that this was a feature of the north-west Indian society during the first millennium BC. It seems highly probable that its roots, like those of the cultural regions, extend back much further. Both these characteristics help to give South Asian culture a peculiar flexibility and adaptability of its own. They ensure that in changing circumstances it has within itself the means and the intellectual and practical reserves to deal with the often catastrophic problems that arise in the rich and varied but unpredictable environment of the subcontinent. When one means of survival becomes impossible there is always another.[37]

Another interesting dimension suggested by Allchin and Allchin is that the unique creative energies of the south Asian region owed itself to the interplay between the northwest, vulnerable to dynamic nomadic interventions, and the more settled south and east, open to gentler interactions through maritime connections, etc.

> The (geographic) north-west/south-east axis is another of the strengths of South Asian culture. Like all major enduring cultures of the world it draws upon the resources and genius of contrasting but complementary regions. In this case it is that of two already highly complex regions. One is the world of oasis linked by nomads of the arid regions to the north-west. The other is the tropical world, much of it potentially capable of carrying dense populations bases on intensive agriculture of the east and the south-east. By successfully encompassing these two aspects South Asia has added a further dimension to itself: the further reserves of intellectual and practical knowledge which have enabled the complex totality to survive. It survives not as a monolith-such cultures pass quickly into fossilized obscurity but as a highly sophisticated structure maintained by many balances and

counterbalances, and capable of lending itself to revival, additions and adaptation.[38]

In the recent opinions of Indus archaeologists such as Jarrige, the marked hiatus between the eclipse of the Indus Civilization (c. 1500 BCE) and the beginning of the Vedic period is now filled by many archaeological finds that entirely change previously held perceptions of the second millennium BCE and instead suggest that there has never been such a spectacular break, but rather a continuum from Neolithic times almost until the present in the material culture of the subcontinent.[39] This idea also comes up in the context of high-tin bronzes discussed in the next section, where evidence suggests that their use in the megalithic period may have culminated from a period of experimentation already begun in the Indus Valley period.

Megalithic High-Tin Bronze Vessels (c. 1000–500 BCE) and Foundations of Metallurgy

Bronze bowls and vessels have been found in Iron Age burial complexes and megaliths of south India, including the Nilgiri hills and Adichanallur, Tamil Nadu state. Since many of these cairns were unearthed in the late 1800s prior to proper excavation without evidence of related habitation sites, their dating has not been firm. Often these vessels exhibit considerable sophistication in execution including extremely thin rims (of less than a millemetre), fine fluted shapes, and knob-bases surrounded by concentric circles. So much so that the skill of the Nilgiri bowls in particular, which are often finely decorated (Figure. 10.1) had previously led to speculations that these were imported by

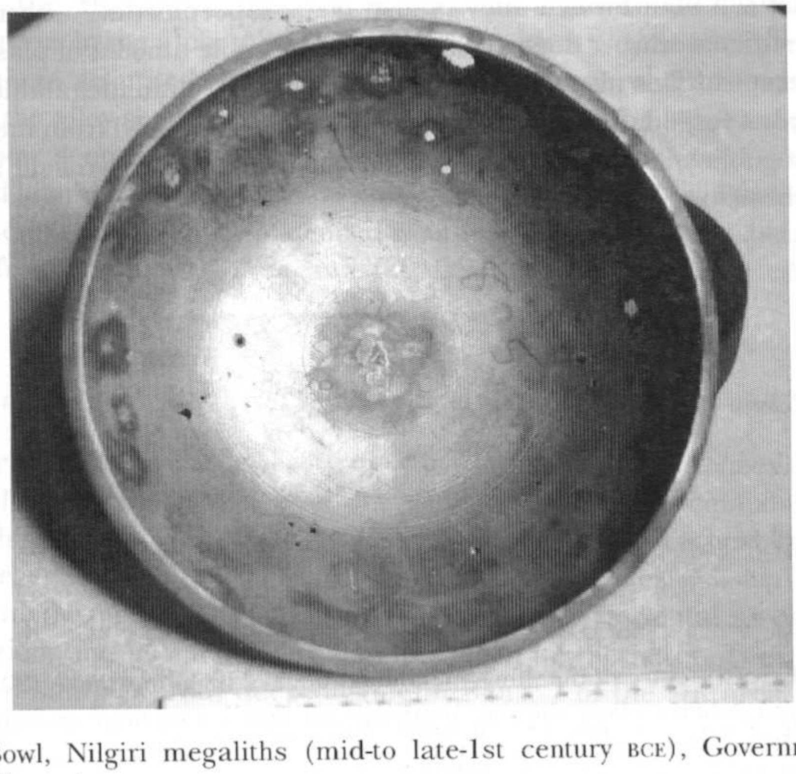

Figure 10.1. Bowl, Nilgiri megaliths (mid-to late-1st century BCE), Government Museum, Chennai.

scholars such as Leshnik.[40] However, the south Indian megaliths bears strong affinities in material culture to that from more recently excavated Vidarbha megaliths from the northern Deccan in Maharashtra, dated from about c. 800 BCE onwards, with a site or two carbon-dated to c. sixth century BCE.[41] Taking this into account and other archaeometallurgical evidence presented here there is now good reason to view the Nilgiri and Adichanallur bronzes as local artefacts. Indeed Allchin and Allchin hypothesized some indigenous developments concerning south Indian megaliths.[42]

Metallurgical investigations and electron probe micro-analysis undertaken by the author on fragments of six bowls and vessels from Nilgiri megaliths and Adichanallur burials from Government Museum, Chennai (formerly Madras), indicated that these are wrought and quenched high-tin bronzes of 23–25 per cent tin, hot forged to extraordinary thinnesses of 0.1–0.2 mm as partly reported in Śrinivasan and Glover.[43] For instance, the microstructure (Figure 10.2) of a thin-rimmed vessel from the Adichanallur Iron Age burials (c. 1000–800 BCE) with 22.9 per cent tin showed β phase from quenching around 650° C with minor alpha islands showing annealing twins from hot forging. Extensive working and annealing in the temperature range of formation of the plastic β phase is indicated by the well-formed and elongated needles of β martensite and the lack of dendritic patterns in the a phase with prominent annealing twins. Such artefacts are well-preserved due to the quenching process, resulting in the retention of a high-temperature intermetallic compound phase. The Adichanallur high-tin bronze vessels analysed by the author include thin well-rounded vessels, thicker jugs and extraordinary wafer-thin strainers no more that 0.2 mm thick with patterns of tiny perforations probably made by diamond drilling practised in Indian prehistory. It appears that the beta bronze alloy is also quasi-superplastic;[44] although it is not a true superplastic material, it does undergo ~~a considerable amount of plastic elongation~~ at high temperature. This also explains how these south Indian megalithic vessels were so extensively hot forged. Paramasivan had also analysed a bowl from the Adichanallur burials whose published micro-structure seems consistent with wrought and quenched high-tin beta bronze of around 23 per cent tin.[45]

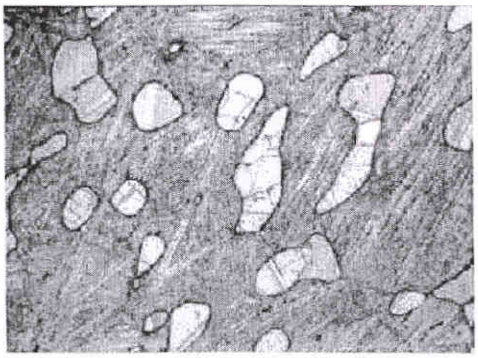

Figure 10.2. Micro-structure of the afore mentioned bowl of high-tin bronze (22.9 per cent tin) from Adichanallur, showing predominant needles of beta martensite and some twinned alpha phase indicating it was hot forged and quenched (400X).

A bowl excavated from the Gandharan Grave Culture of Taxila in Pakistan, c. 1000 BCE, investigated by the author (courtesy Ian Glover and the Pakistan Archaeological Survey) by scanning electron microscopy was also a high-tin beta bronze with 24 per cent tin, with a rim thickness of 1–1.5 mm.[46] Intriguingly three samples excavated in the 1930s from Mohenjodaro (480–1), the Indus Valley site (c. 2500 BCE) in Pakistan, were found to contain 22.1 per cent tin, 22.2 per cent tin and 14 per cent lead, and 26.8 per cent tin respectively.[47] Kenoyer mentions an intriguing literary reference to export of tin from 'Meluha', thought to be the Indus region.[48] Metallographic investigations and electron micro-probe analysis on two vessel fragments from the Vidharbha megaliths excavated by Deccan College undertaken by the author at the Freer Gallery of Art, Smithsonian Institution, indicated that they were of wrought and quenched bronze with 18 per cent and 21 per cent tin. Tin sources are reported to have existed in the regions of Afghanistan as well as some minor ones in central eastern India.

Well-dated early high-tin bronzes have included bracelets and several bowls from sites in Thailand, particularly Ban Don Ta Phet, c. fourth century BCE.[49] However, the findings reported above from various parts of the Indian subcontinent, some going back to the earlier part of the first millennium BCE, seem to predate these. The trace elemental composition of the south Indian examples also differs sufficiently from Thai ones as reported in Śrinivāsana and Glover.[50] The Thai vessels bear similarities to the Nilgiri vessels in the bases with raised knobs, which are still seen in some of the recent vessels from Kerala, as also observed by Ian Glover on a field trip in 1998 with the author. Compared to the Indian megalithic vessels, especially from the Nilgiris and Adichanallur, the Thai bowls reported by Rajpitak seem smaller, often with as-cast dendritic patterns in the alpha phase, which suggest that they were either cast to shape or worked only to a limited degree before quenching, whereas the quasi-superplastic properties of the alloy seem to have been best exploited by the Nilgiri and Adichanallur smiths.[51] It now seems plausible to postulate that the technique of making wrought and quenched high-tin beta bronze bowls may have had local roots in Indian protohistory and could then perhaps have influenced southeast Asia. Finds of beta bronzes are also known from medieval Korea and the Islamic world as reported by Melikian-Chirvani.[52]

Tin in Indus and Megalithic Periods and in Relation to Gold, Lead and Silver

When one tries to trace back the antiquity of the Indian high-tin bronzes, the finds from the Indus Valley site of Mohenjodaro of a few samples of the composition of binary bronze of a high-tin content would surely rank amongst the earliest reported in the world.[53] However, without metallurgical study it cannot be established if these were intentionally made quenched beta bronzes, or merely accidental as-cast bronzes of this composition, and as such it remains likelier to be the latter. These are reported from corroded samples from deep digging in Block 7 of the DK area and Mackay's notes suggests that he did not doubt that these were from an Indus Valley context (c. 2000 BCE). Sample DK 9722 at 30 feet below datum had 22.2 per cent tin, with scarcely any lead at 0.86 per cent, typically matching the composition of high-tin beta bronze; sample DK 9567 had 26.9 per cent tin with no lead found at 26.8 feet below datum, while two more samples had 19 per cent tin with no lead.

In fact, if we look at a compilation of some 140 analyses of objects from Indus Valley contexts in Chakrabarti and Lahiri a noticeable trend is that about 30 objects from Mohenjodaro have tin contents over 5 per cent and contain no lead, and about 24 have more than 8 per cent tin and no lead, while only 4–5 objects have more than 2 per cent lead.[54] Indeed, overall, out of 30 per cent bronze objects from different Indus sites with over 8 per cent tin, only one sample from Mohenjodaro any substantial lead, of 14.9 per cent, and that is in fact a bronze with 22.1 per cent tin, which may suggest that it could have been deliberately added with the intention of experimenting to overcome the brittleness of this alloy in the as-cast state, although it is workable at high temperatures as discussed before. This suggests that the Mohenjodaro craftsmen may have gone some way towards experimenting with the properties of bronze of higher tin contents, with and without lead, although it is not known if they ever arrived at the true martensitic quenched high-tin bronze alloy. It must also be pointed out that, given the developed Indus system of chert weights and measures it would have been possible to measure out the fairly precise amounts of tin for high-tin bronze.

The use of lead metal is also seen in the form of what is often described as a plumb bob, i.e., a lead ball of about an inch in diameter so that it appears that the alloying of tin and lead would have been intentional with some knowledge of the properties.[55] Mackay however suggested that 'the metal workers seem never to have realized that if it (lead) had been used sparingly as one of the alloys of bronze casting could have been facilitated.' He goes on to suggest that 'it is indeed possible that much of, if not all, the silver used was procured from lead ore. The use of lead may suggest the attempt to utilize a waste product.' However, contrary to Mackay's opinion, the trend of certain higher tin bronzes containing more lead than lower tin artefacts suggests that the properties of alloying lead to bronze to make it more castable was probably known. Even so, it is certainly true that nothing akin to the comparatively enormous leaded bronze Chinese ritual vessels (c. 1700 BCE) are found to suggest that either that properties of casting leaded bronze were fully explored or that tin and lead were available in abundance.

The sources of tin, a scarce commodity in India today, has been an enigma since tin deposits in the Indian subcontinent are sparse. However it must be remembered that deposits that would be termed as uneconomical in industrial terms today could have been sufficient for small-scale, labour-intensive mining, while placer mining of tin leaves no traces. For the finds from the Indus Valley and Taxila, Afghanistan, seems a plausible source of tin with some stannite and cassiterite deposits, while Misgaran in Herat is reported to show some evidence of early exploitation.[56] Jarrige points to the influences from late Bronze Age Bactria and Magria in Afghanistan during the later Indus Valley period, and it remains a possibility that the high-tin bronzes reported at Mohenjodaro are linked to developments in these regions.[57] It is also significant that Kenoyer points out that the goods being traded out of Meluha or the region of the Indus to Dilmun and Magan, i.e., modern Bahrain and Oman, included tin or lead together with copper, gold, silver, carnelian, pearls, ivory and peacocks, which may reinforce the idea of the Indus region being a key area for ancient experimentation with the use of bronze, as suggested by the few finds of bronze of a high tin content.[58]

Indeed, the author's investigations on south Indian material surprisingly offer more evidence for local sources of tin than previously suspected. For one, the high-tin bronzes beta bronzes from south Indian megaliths had sufficiently different patterns of trace elements from those from Thailand to suggest different sources of metal for the Indian examples.[59] Interestingly, investigations by the author on slags from the ancient mining region of Kalyadi within the Hassan district of Karnataka indicate that these are bronze smelting slags with up to 7 per cent tin from co-smelting copper and tin ores due to the presence of metallic iron, rather than casting slags from alloying copper and tin, which points to exploitation of indigenous sources of tin.[60] Maloney mentions that tin was one of the items sent out of the Karnataka coast in Solomon's times along with peacocks and naves (i.e., the pre-Christian era).[61]

It has been postulated that gold from the Karnataka region collected from the surface by Neolithic cultures of the mid third millennium BCE reached the Indus region.[62] An intriguing find reported in *The Hindu* in 2006 was of a Neolithic stone celt from Mayiladuthurai district in Tamil Nadu, apparently with the Indus script as identified by Iravatham Mahadevan.[63] Preliminary field surveys made by the author in north Karnataka in the Hutti-Maski region in 1991 indicated extensive old workings for gold in the region where practically every outcrop had old mining galleries with large mullacker fragments lying around from ore crushing activity. Radiocarbon dates on timber from an old mine over 200 metres deep in Hutti indicate that deep hard rock mining was carried out by the mid fourth century BCE, which appears to be the deepest old gold mine in antiquity.[64] The Jalagarus of the Dambal region are described in nineteenth century accounts of Foote as a sect of people who carried out alluvial washing and panning for gold when the heavier gold got washed downstream from the auriferous hills after the rainy season.[65]

Some sparse placer tin had been reported with alluvial gold in the Dambal region of the Karnataka region.[66] Given the extensive evidence for ancient exploitation of gold in north Karnataka, it is not impossible that some local tin ores could have also been exploited.[67] It is thus may not be coincidental that the high-tin bronze vessels found in South Indian burials such as Adichanallur and Nilgiris (first millennium BCE) also occur with finds of gold ornaments. Bronson points out that 'traditional tin and gold mining have many similarities. Owing to its density and chemical resistance, tin oxide ore could practicably be recovered from alluvial deposits by panning and ground-sluicing methods like those used for mining gold. Deposits with a tin content in the 0.1 per cent range could therefore be worked profitably. The multiplicity of these deposits within the tin-bearing areas, along with the simplicity of equipment needed to sluice out and smelt the ore, meant that productive units stayed numerous and small. As late as the 1880s the bulk of the tin in world commerce was produced by small firms using methods that were essentially preindustrial.'[68] Eastern India also has some tin deposits in the Hazaribagh region, where Mallet observed the pre-industrial smelting of tin by local tribals in furnaces resembling shaft furnaces for iron smelting. What the above suggests is that tin mining did not need very rich deposits and could have been undertaken on a small scale.

The rich finds of gold jewellery from the Nilgiri cairns are of particular interest. They have been dated from the early or mid first millennium BCE to CE, showing considerable diversity.[69] Although they are not in themselves technologically distinctive enough to justify being included in an essay related to the foundations of science, they nevertheless present an interesting case study since their distinctive artistic styles have led to questions of their origins; whereas it is argued here that they are not all that inconsistent with the techno-cultural milieu that seems to have prevailed in Tamil Nadu around this time.

The sophistication of finds from the Nilgiri cairns has generally fuelled speculations about imports such as from Iran.[70] Some general Etruscan/Hellenistic influences are to be detected in the use of the technique of gold granulation whereby surface tension was used to turn melted gold filings into spheres as also found in jewellery from Taxila. However, at least one commentator, Robert Knox, generously conceded that although astonishing objects not known archaeologically elsewhere in India come from the Nilgiri cairns, there is enough that is distinctive or diverse enough about them to suggest local styles. Knox is persuasive that in the earrings, pendants and other ornaments from the Nilgiri graves the local style becomes apparent, whereby these are

> well made objects, probably made of local gold, constructed with skill and imagination, neither of which qualities need have been beyond the reach of a people who were original and talented enough to produce the unique Nilgiri ceramic assemblage, the iron tools and, if our imagination can run to it even the bronze vessels.

Indeed, ~~this paper points to evidence suggesting the likelihood~~ of the Nilgiri bowls being of local origin as well as the possibilities of exploitation of local gold.[71]

It is well recognized that a keen interest in observing nature and natural phenomena has played a major role in the foundations of science. As far as Indian metallurgical heritage is concerned, it is worth remarking about the strong sense of botanical observation reflected in early jewellery, including the Nilgiri material, from Tamil Nadu: mirroring the rich poetry of the Tamil Sangam era (c. third century BCE to CE) that evokes local fruits and flowers such as *kurinji,* which blossoms once in 12 years in the Nilgiris, a region rich in unusual flora and biodiversity. Knox pointed to the 'ear-rings in the shape of stylised flowers not known elsewhere archaeologically' from the Nilgiri assemblage of the mid to late first millennium BCE. A scientific sense, perhaps, is also suggested by the ear-rings in the shape of perfect geometric octahedrons. These also distantly echo of pyramidal ear-rings worn by Kutchi nomads. On the whole, the Nilgiri jewellery is chunky and rather three-dimensional compared to flatter Etruscan examples. It bear the marks, though greatly separated in time, of the distinctive chunky jewellery of south India such as the remarkable, Picasso-esque 'pampadam' ear-rings traditionally worn by women from Salem in Tamil Nadu. Nature motifs in the Nilgiri assemblage include an intricate pendant with crescent moon motifs, a granulated flower motif (Figure 10.3) and a peepul leaf motif. Another outstanding early example of this idiosyncratic 'three-dimensional' gold jewellery from Tamil Nadu

Figure 10.3. Ear-ring in the form of a granulated flower motif from Nilgiri cairns, c. mid first millennium BCE. Copyright the Trustees of The British Museum.

is a ear-ring from Souttoukeny of the second century BCE, which depicts a typical local spiked prickly fruit, now in the Musee Guimet in Paris.[72] The artistic inspiration from botanical specimens continues in Indian ear ornaments; for example Waltraud Ganguly has studied ear-rings in shapes such as a clove (Figure 10.4) and a coiled palm-leaf.

As for the gold deposits that could have then been exploited, the Nilgiri hills and Wynad bordering the present states of Tamil Nadu, Kerala and Karnataka comprise some sparse hard rock and alluvial gold deposits. Although they are not viable for commercial exploitation they continue to be illegally mined/panned by local Kurumba tribes. These include deposits adjacent to Wynad on the border with Kerala and within the Nilgiris themselves in Gudalur. The author together with her husband Digvijay Mallah, from the local Badaga community of the Nilgiris, had explored some of the old gold workings in the region of Gudalur, now in the Sea Fort tea estate, and came across Kurumba tribal children engaged in hard rock mining for gold and panning from associated streams for alluvial gold. Notwithstanding the issue of child labour and hazards of mercury poisoning, one could not help being impressed by the great skill exhibited by the Kurumba children aged no more than nine to twelve in the panning and mercury amalgam extraction of gold. They first panned the alluvial sand in large

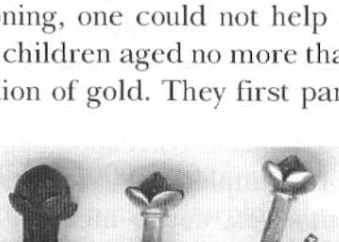

Figure 10.4. Clove motif ear-rings. Photograph courtesy of Waltraud Ganguly.

wooden pans to concentrate fine specks of sand rich in gold and then added a blob of mercury to create an amalgam with the gold. Then this blob of amalgam was placed on a small leaf and heated to sublimate the mercury, leaving behind a small globule of gold. In this way they were able to retrieve even very trace quantities of metal, which commercial prospectors would find quite uneconomical to extract. The Kurumba tribe was traditionally believed to have had magical powers apart from knowledge of mining and metallurgy. Such indigenous knowledge may have played a significant role in Indian antiquity.

Musical Properties and High-Tin Bronzes

The making of wrought and quenched high-tin beta bronze vessels, gongs, cymbals and ladles was first documented in 1991 by the author in Palghat district of Kerala. Micro-structural investigations by the author on two bowls from Payangadi and Trichur bought in 1991 confirmed that the largest concave bowl, of 25 cm, 8 cm deep and 1.4 mm rim thickness, were made out of a flat circular ingot of 22.5 per cent tin of a diameter of only 15 cm, and 1.5 cm thick, by forging in cycles of hammering and annealing followed by quenching between 600–700°, all in the α+β phase field.[73] When polished, the inner surface of quenched beta bronze bowls take on a brilliant golden lustre that contrasts nicely with the exterior quenched skin. Such vessels were described in colloquial Tamil or Malayalam as *talavettu* or musical vessels due to the tonality of the β-martensitic alloy. The author's late grandmother, Janaki Subban, interviewed in 1991, said that the *talavettu* were preferred to brass for storing food due to the relative non-toxicity of a high tin content and the alloy's corrosion resistance. She added that food was ~~not heated in such vessels, which~~ could be due to the formation of the embrittling lower temperature phase upon cooling. A subsequent field visit made in 1998 with Ian Glover indicated that while high-tin bronze vessels were still made in parts of Kerala, the large and deeply concave bowls that the author observed being made in October. 1991 at Payangadi were no longer being made.

Outside the Indian subcontinent there seem to be few ethnographic parallels for ancient high-tin bronze bowls. Although quenched high-tin bronze gong-making in the recent past has been documented in the Philippines and China,[74] the degree of working described therein seems less. Consequently, indigenous origins now seem highly plausible for the ancient south Indian high-tin bronze vessels due to the close links with the modern Kerala process: such as the shared concentric rings made using a hand-turned lathe at Payangadi, the faint spiral hammer marks seen even on knob-based bowls, and the flat disc-like bases corresponding to the original diameter of the ingot shared with some ancient examples.

While the megaliths themselves, not to mention the megalithic high-tin bronze bowls, remain an enigma, a matter for speculation concerns the function of these elegant megalithic high-tin bronze bowls. One possibility could have been some ritual function. Indeed the raised knob-base surrounded by rings and the floral lotus patterns on some Nilgiri bowls and links with bowls from Thailand have made some perceptive commentators such as Glover[75] to speculate about ritual associations with Buddhism.

This is seen from the decorations of the raised knob-shaped base and rings representing mount Meru in the centre. In practical terms the functionality of high-tin bronze for storing food lay in its lower corrosive properties as mentioned by artisans in Kerala. However, a third possibility is that the vessels may even have been appreciated for their musical significance even as far back as the megalithic period since the quenched high-tin bronze alloy is found to have good musical properties and is used in cymbals even today (Figure. 10.5). Even today in Tamil Nadu, high-tin bronze vessels are used for playing the intricate traditional Jalatarang in the classical Carnatic music style.

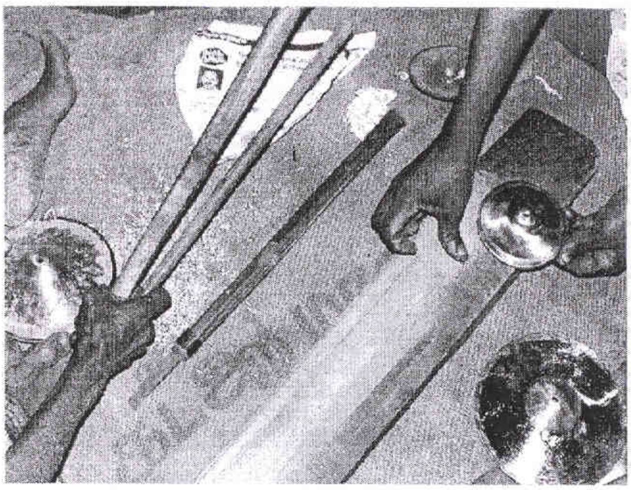

Figure 10.5. High-tin beta bronze musical cymbal being made in Kerala.

The grounds for speculating that the high-tin bronze alloy's musical properties may have appealed even in megalithic times come from recent publications by Boivin suggesting that clusters of rocks with depressions from the Neolithic site of Kupgal in Karnataka in southern India (c. 3000 BCE) could have been used for making ringing or percussion sounds.[76] In February 2006 the author visited this dolerite massif at Kupgal where boulders with man-made depressions are found interspersed amidst abundant Neolithic rock art, which were found to give off notes of different high-pitched to sonorous tonalities when hit with one of the oval-shaped Neolithic dolerite adzes found lying around. One location in particular was interesting, where there was a clearing flanked by a large 4 feet by 6 feet wide vertical rock face with several depressions, giving off a range of ringing tones and this spot overlooked a large piece of Neolithic rock art showing a set of dancers with linked hands. It seems extremely likely that this clearing was used as a spot for dancing set to the 'music' of the rocks. The spectacular megalithic site of Hirebenkal (c. 1000 BCE) consists of innumerable dolmens and chambers tombs made of highly resonant porphyritic granite slabs as noted by the author during a visit. Amidst these are some granite slabs placed at an incline which when hammered are said to resound into the valley.[77] Such ideas also resonate in the 'musical' stone pillars of the fifteenth century Vijayanagara site of Hampi. Thus the concern with musical materials might have been one of the reasons for the preference of high-tin bronze.

High-Tin Bronze Water Clock as an Example of Hindu Instrumentation

Although we have commented on the relative paucity of actual physical evidence of instruments from within a Hindu context, the author has found some highly interesting evidence for the use of high-tin bronze in a highly skillfully made wafer-thin water clock (Figure 10.6). The clepsydra is said to find mention in the *Vedāṅga-Jyotiṣa*, the *Arthaśāstra* and the *Sardulakarn-avadana*, and is described to have been like a water jar with a hole at its bottom from which water flowed out in one *nadika* or one sixtieth of a day. The *ghati yantra*, on the other hand, is a sinking water clock with a hole at its bottom. As it floats, water flows into the bowl and sinks after a certain time interval. The Chinese Buddhist traveller Yijing (635–713 CE) is said to have recorded the use of such a clepsydra in India.[78]

Figure 10.6. Water clock, probably of high-tin bronze, Kerala.

As for the purpose of water clocks, Sarma points out that Brahmanical rituals required stop watches to regulate their course.[79] He gives a description of the type of *ghati* or sinking water clock frequently used in India at least from the early eleventh century until the arrival of mechanical clocks from Europe. Here, a hemispherical copper vessel (*kapala*), six digits high and with a capacity of about 3.1.3 litres (60 *palas*) with a hole at the bottom to admit a gold pin four digits long and weighing approximately 0.183 gm (3.33 *masha*), was placed on water. The vessel sank in one *ghaṭi* or *ghaṭikā* sixty times a day. Such a vessel has been used until recently in some temples and orthodox rituals.

This type of *ghaṭi yantra* was apparently widely used until recently, and indeed the water clock in Fig. 10.6 is this type of sinking water clock with a hole acquired by the author from Kerala. It demonstrates highly skilled manufacture and appears to have been made of quenched high-tin bronze from the shiny patina and the extraordinary rim thinness of less than a millimetre, which the author is able to recognize after having looked at several examples. A somewhat similar looking clepsydra is illustrated in Ohashi in the Rao Madho Singh Museum, Kota, Rajasthan.[80] Michel Danino showed a miniature painting of mathematician Bhāskarācārya's daughter, Lilāvati, herself an accomplished mathematician, waiting in vain for her *ghaṭi yantra* or water clock to fill up since it has a pearl stuck at the bottom. It is something of an allegory for the conundrum of timelessness and eternity in Indian thought whereby in Danino's poetic words (during his lecture in 2003), 'one loses the sense of time and drifts into a contemplation of this mysterious universe.'

INDIAN TEXTS AND EVIDENCE OF METALLURGICAL SKILLS

In an overview of the history of chemistry and alchemy in India from pre historic to pre-modern times, Deshpande[81] categorized various phases of history corresponding to the development of chemistry and alchemy as pre-Vedic (including Harappan) (c. 2500–1500 BCE), Vedic (1700/1500–500 BCE), post-Vedic or Buddhist (c. 500 BCE–600 CE), and Tantrik or Alchemical (700–1300 CE). She suggests that it was really in the Tantrik or Alchemical phase that attempts were made to give explanations for observed processes and to invent new processes through experimentation, analysis and replication, which form the backbone of scientific processes as understood in the modern sense. According to her, in this period especially small-scale alchemical experiments were carried out particularly on precious metals followed by attempts to explain phenomena using then established alchemical theory. Such experimentation was attempted especially by practitioners of Āyurveda, the ancient Indian medical and alchemical system. Numerous Tāntric texts on Rasāyana, which flourished during the medieval period, dealt particularly with alchemy. Rasāyana literally refers to medicines derived from mercury and was especially concerned with rejuvenation and the making of elixirs.

From the early historic period (c. 500 BCE–600 CE) come some landmark texts that give some insights into metals and related uses in alchemy and medicine, such as ~~the political treatise of the *Arthaśāstra* (c. fourth century BCE)~~ compiled by Kautilya, the prime minister of the Mauryan emperor Chandragupta; an Ayurvedic text on medicine, the *Caraka Saṁhitā* attributed to Caraka of the first century CE; the *Suśruta Saṁhitā*, attributed to Suśruta, c. second century, on surgery; the *Rasaratnākara* (c. fourth century), attributed to the great Indian alchemist Nāgārjuna; and the Gupta sculptural and artistic treatise of the *Manasara* (c. fourth century). The *Manasara* described in some detail the processes involved in the casting metal images.

The *Arthaśāstra* has a chapter related to the working of the ministry of mining and related factories. It lays down some guidelines for the ministry of mining and the mining inspector especially in the assay, identification and beneficiation of ores, of distinguishing, locating and treating ores and identifying the characteristic features of gold, silver, copper, lead, tin and iron ores.[82] The term *arakuta*, which is used in tenth century Chola inscriptions for brass, finds mention in the *Arthaśāstra*. In a paper by the author, it was pointed out that 'Kamsyatala', mentioned in the *Arthaśāstra* could be the term for high-tin bronze since the term *kaṅsa banik* is used to describe the wrought bell metal workers of Orissa.[83] Tin ores are referred to as *kastira*, related to the Greek derived term cassiterite. The alloying of copper to gold to harden it finds mention in the *Arthaśāstra* as does the process of fire gilding using the mercury amalgam technique. One of the varieties of gold described in the *Arthaśāstra* was *Rasaviddham*, i.e., very likely gold obtained from treatment with mercury. The *Suśruta Saṁhitā* describes numerous surgical instruments (very likely ferrous or probably even of steel) and classified arsenic compounds as poison.

Nāgārjuna, who is thought to have lived around 400 CE, is said by the seventeenth century biographer, Tārānātha to have been born in a south Indian Brāhmiṇ family and later converted to Buddhism before becoming a renowned alchemist. There is a famous Buddhist site, Nāgārjunakonda, in Andhra Pradesh attributed to the Ikṣvāku dynasty (c. 400 CE). Nāgārjuna authored the *Rasaratnākara* devoted to the extraction and purification of metals.[84] There are some important references related to zinc in Nāgārjuna's writings of *Kuṭilasaṁkāsam*, i.e., metal resembling tin, while calamine was described as *rasaka*.[85] In Nāgārjuna's comment, 'What wonder is that calamine ... oasted thrice with copper converts the latter into gold?' an unambiguous reference to the manufacture of brass by the cementation process is made. In this process, the zinc vapour produced by heating zinc ore of calamine would result in the production of zinc vapour, and this vapour would be absorbed into copper in the solid state to yield brass of a composition not exceeding about 30 per cent. Nāgārjuna seems to also recount some process related to the smelting of zinc from calamine in a closed crucible to yield a metal in the appearance of tin, i.e., zinc in the following passage: '*Rasaka* or calamine is digested repeatedly with fermented paddy-water, natron, clarified butter and mixed with wool, lac, *Terminalia chebula* and borax, and roasted in a covered crucible when it yields an essence of the appearance of tin.'[86]

Subsequently it was the eleventh to fourteenth century period that produced numerous alchemical and iatro-chemical texts in Sanskrit, related to *Rasāyana śāstra* or alchemy and related metallurgical processes. The *Manasollasa*, or *Abhilāsitartha-cintāmaṇi* written by the Chalukyan king Someśvara of the twelfth century CE from southwestern India gives a detailed description of the process of making metal icons by the lost wax casting process known as *Madhuchchhisthavidhāna*. The *Rasopaniṣad*, one of the largest Sanskrit texts in alchemy with over 2500 verses was written around the eleventh–twelfth centuries in southern India, and dealt primarily with the transmutation of metals and especially the making of gold and silver-coloured amalgams involving metals from mercury to tin. According to Deshpande, the *Rasopaniṣad* indicates that alchemists were familiar with the properties of tin and its existence in the two physical modifications of white and grey tin; that tin has a low melting point and resembled silver in its pure crystalline form. The text also indicates that they knew that the alloying of a little silver to pure tin inhibited the transformation of white tin to grey tin. Such a familiarity in a south Indian text with the use of tin is consistent with the skilled and continuing traditions of using high-tin bronzes already noted in this region. *Rasārṇava*, said to be authored by a Hindu Śaiva, related to methods attempting to fix mercury, transmute metals and make elixirs. The *Rasaratnasamuccaya* of Vagbhatta, attributed to the thirteenth–fourteenth century, is a landmark iatro-chemical Indian text, addressed to Bhaisajyaguru or Buddha as physician. This text yields valuable and extensive information on the process of zinc smelting, which correlated well to the archaeological evidence at Zawar, which is also the earliest known from anywhere in the world.[87] The eleventh chapter deals extensively with mercury, its purification, fixing and incineration.

Zinc Smelting

Of great relevance to the foundations of science is the fact that it was in India that metallic zinc was first isolated and where high-zinc brass alloys were first used in the pre-industrial period. Of the metals used in antiquity zinc is one of the most difficult to smelt since zinc metal is very readily oxidised and volatalizes at about the same temperature of around 1000°C which, is needed to smelt zinc ore. As a result it would form as a vapour in the furnace that would immediately get reoxidised and hence lost. Hence metallic zinc is seldom reported in antiquity.

However, in India there is unique evidence for the extensive and semi-industrial production of metallic zinc at the Zawar area of Rajasthan by at least the twelfth century CE. The pioneering fieldwork and studies of the team of late K.T.M. Hegde of Baroda University, Paul Craddock of British Museum, Lalit Gujjar and others of Hindustan Zinc have put these remarkable achievements on the world map, especially with the expertise and authoritative writings of Paul Craddock. An ingenious method was devised of downward distillation of the zinc vapour formed after smelting zinc ore using specifically designed retorts with condensers and furnaces, so that the smelted zinc vapour could be drastically cooled down to about 500° to get a melt that could solidify to zinc metal. The furnaces excavated at Zawar consisted of a thick perforated brick plate which effectively divided the furnace into two chambers (Figure 10.7), the top would be packed with charge and fired and the cool bottom would be the part that the smelted zinc vapour would be condensed. The aubergine-shaped retorts (Figure 10.8) were stuck vertically through the perforations, such that the top parts were filled with charge, while the stem forming the condenser led into the bottom cooler chamber so that the vapour could condense through the stem and drip and be collected in vessels placed at the bottom.[88] Indeed the remains suggest that the sophistication of zinc production Zawar was almost on an industrial scale in an era preceding the Industrial

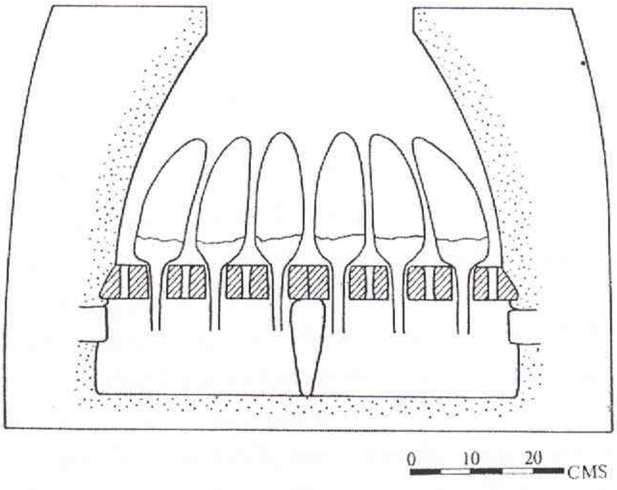

Figure 10.7. Schematic diagram of zinc smelting furnace, Zawar, Rajasthan. (Courtesy of Brenda Craddock.)

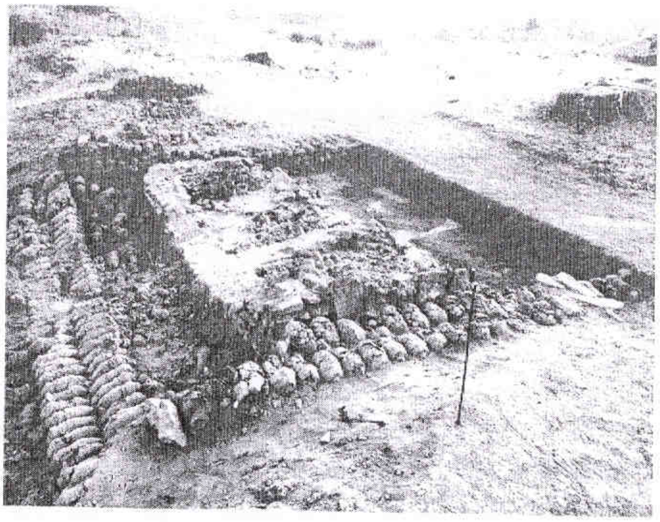

Figure 10.8. Zinc smelting retort from Zawar, Rajasthan. (Photograph courtesy Paul Craddock.)

Revolution, with each furnace having held about 36 retorts with no less than 252 furnaces being simultaneously fired. Zinc mining at Zawar continued on a large scale during the Moghul era, although this activity seems to have died out by the seventeenth century. Extensive zinc mines are found at Zawar with huge mining galleries, some of which have been carbon dated back to about 2,000 years, i.e., the beginning of the Christian era.

The *Rasaratnākara,* a Sanskrit text ascribed to the great Indian scientist Nāgārjuna, of the early Christian era, describes the Indian method of production of zinc, i.e. *tiryakpatana* or downward distillation, while other early Hindu and Buddhist alchemical texts also describe similar processes such as the *Rasaratnasamucchaya.* A description of the cementation process is also given in the Sanskrit text of the *Rasaratnākara.* Although the organic prescriptions in the *Rasaratnasamuchhaya* may sound scientifically improbable, they have been found to remarkably correlative with the finds at Zawar down to the description of the retort as being aubergine-shaped, the use of salt[89] which would have served as a sintering agent, and so on.

Elsewhere in antiquity brass was largely made by the cementation of zinc ore with copper, involving the diffusion of zinc vapour into copper in the solid state, which would not yield a composition of brass with more than about 28 per cent zinc. This involved the heating of a mixture of calcined calamine of zinc carbonate with charcoal with pieces of copper in crucibles, with the temperature controlled to not more than about 1000° such that the calamine would have been reduced to zinc vapour without melting the copper and the zinc vapour would diffuse into the copper surface in the solid state. Thereafter the brass was melted and poured into moulds.

Indeed the earliest known evidence for the use of brass made by alloying zinc metal to copper comes from brass objects with about 34 per cent zinc excavated from the ancient Buddhist site of Taxila (c. fourth century BCE), or Takshashila, in the northwestern part of the Indian subcontinent. The high zinc content over 28 per cent indicates that the process used was of alloying metallic zinc with copper rather than the production of brass by cementation of zinc ore with copper. A metallic zinc ingot with a Deccan Brahmi inscription studied by the author in a technical finger-printing exercise could be attributed to the fourth century CE from the Andhra region using lead isotope finger-printing.[90] This zinc coin ingot was exhibited with a batch of coins in the Science Museum in a show on 'Science in India' in the 1980s and came from the personal collection of the late Nigel Seeley, connoisseur and erudite expert on the technical aspects of cultural heritage. This coin represents some of the earliest evidence anywhere in the world for metallic zinc and it was found in southern India. Brass images and votive artefacts of Hindu, Buddhist and Jaina affiliations were made in various parts of the Indian subcontinent.

Another remarkable artistic innovation in the use of metallic zinc by Indian metalworkers of the past was the highly elegant *bidri* ware, a high-zinc alloy with 2–10 per cent copper, with the black patination being formed by immersion in a mixture of potassium nitrate and ammonium chloride, which was inlayed in silver. These were in vogue under the Muslim rulers of the Bidar province in the Hyderabad region of southern India from at least the sixteenth century. Several impressive vessels, ewers, pitchers, vessels, ewers and *huqqā* bases, etc., were made of *bidri* ware with Persian influence in the fine geometric and floral patterns and inlayed metal work.

In Europe, commercial zinc smelting operations were first established in Europe by William Champion in Bristol in Britain in the 1740s, following which it was industrially produced. Interestingly, the method of production adopted by downward distillation bears a strong resemblance to the Zawar process, which it could well have been inspired by as pointed out by Craddock and Craddock et al.[91] Thus Indian metallurgists can justifiably be seen to have pioneered the difficult technology of zinc smelting and championed the introduction of metallic zinc into the modern world.

In seeking to understand why and how the technology of zinc smelting was mastered in India before most of the world, this author would like to propose that one explanation could be that notions of 'distillation' and 'sublimation' were deep ritual and aesthetic pre occupations going back to ancient times in India, and zinc smelting would have followed out of familiarity with such processes. The abundance of perforated jars from the Indus period has raised speculation about their use as incense burners involving the sublimation of materials. The distillation and extraction of materials for ritual purposes is also seen from the soma drink associated with Vedic sacrifice. The *Rasaratnākara,* a Sanskrit text ascribed to the Indian scientist Nāgārjuna, during the early Christian era, describes the method of production of *rasa/rasaka* by '*tiryakpatana*' or downward distillation, which can be identified with zinc. Of course, the preoccupation with mercury as an elixir and hence of the related process of mercury distillation also has a long history in the subcontinent. Curiously, there is a striking analogy with the concept of *rasa,* the same term found in the *Nātyaśāstra,* the Indian text on dramaturgy and dance, which can be qualified as a distilled essence of an aesthetic experience or perception of sublimation that has quite literal parallels with the process of zinc smelting. One can thus speculate whether the aesthetic concept of *rasa* predated the technological nomenclature, whereby a technical process has been interpreted using an aesthetic concept. Lead isotope ratio analysis undertaken by the author of an early historic zinc coin from the collection of the late Nigel Seeley corroborated a possible Deccan provenance, showing a droplet-like shape as produced by downward distillation.

The astrolabe came into India through Islamic, influence with an early imported example of a true planispheric astrolabe being a Damascus astrolabe of 1204 preserved in the Rampur State Library in Rajasthan. Lahore became a famed centre for the making of superlative brass astrolabes under families of instrument makers like those of Shaikh Allah-Dad (1570–1660).[92] Because high-zinc brass can be cast easily and is higly ductile, it could take on the precise and minute details required for astrolabe making.

COSMIC ALCHEMY AND METALS: THE TAMIL NATARĀJA BRONZE AND COSMIC DANCE

It is interesting that there are examples from the mists of antiquity that the inter-linkage of metallurgy, alchemy and astrology (which can perhaps be viewed as an incipient stage of astronomy) formed one of the foundational aspects of metallurgy. An early connection between man, metals and antiquity was provided by meteoric iron. Iron rarely occurs on earth in the elemental form but is found widely distributed as iron ores. The most common examples of metallic iron on earth are in fact of meteoric origin with exceptionally large examples known as siderites. The first use of iron by man was also meteoric, according to evidence from Egypt of the third millennium BCE. Meteoric iron was referred to as 'iron from the heavens' by the Egyptians, while Hittite records (1700–1200 BCE) suggest that they were aware of two different types of iron, the black one from the heavens and the other from the earth. Metallurgy has also been known as siderurgy, harking back to the connection made in early antiquity to metallic objects falling from the sky.

In the time of the ancient Babylonians, seven metals were known, namely gold, silver, copper, iron, tin, lead and mercury. The Babylonians linked these seven then known metals to corresponding mobile celestial bodies of the sun, moon and five planets, which also corresponded to the seven days of the week. These also drew from Egyptian traditions, whereby Ammon, the god of the sun, was written with the hieroglyph of a circle with a dot where the circle means perfection and the dot indicates that the circle is not empty. The hieroglyph of the Egyptian moon Goddess Isis was a crescent, which was also the symbol for silver. The western alchemical tradition drew from these ancient Babylonian ideas, with each metal being associated with a celestial body, the sun, moon and planets. These symbols for metals that medieval European alchemists and astronomers used were given their final form in the eleventh and twelfth centuries CE.[93]

Within the Indian tradition, a most interesting case for exploring connections between astronomy and metallurgy comes from the Natarāja bronze of the dancing Hindu god Śiva or King of Dance as described by Bilimoria,[94] which was especially patronized by the powerful Chola dynasty, which ruled from Tanjavur in Tamil Nadu.

Amongst the best known of Indian sculptural expressions are the metal icons of southern India, especially of the early medieval Chola Tamil kingdom. Art historian J.C. Harle described early Chola bronzes as 'the finest representations of godhood.'[95] The celebrated Natarāja metal icon was eulogized by master sculptor August Rodin in an essay 'La Dance de Śiva'. The Natarāja metal icon has also uniquely appealed to the modern scientific temperament as illustrated by the writings of geologist-turned art historian Ananda Coomaraswamy[96] on the 'Cosmic Dance of Śiva', which he hailed as 'poetry but nonetheless, science', and we have mentioned before the writings of Carl Sagan and Fritjof Capra.

To trace the evolution of the rich metal industry of medieval southern India, archaeometallurgical and scientific investigations were made by the author on a comprehensive range of copper alloy artefacts. While the iconography of South Indian images has been well studied, there has been a lack of consensus amongst art historians on stylistic, chronological and provenance attributions due partly to the fact that most bronzes are not inscribed, so that it is relevant to explore objective technical criteria for making such attributions. In the first and most comprehensive technical and archaeometallurgical study either in India and abroad on South Indian images, the author undertook technical analysis as doctoral research[97] for the purposes of finger-printing, authentication and stylistic re-assessment of 130 artistically important images sampled from the collections of the Government Museum, Chennai (70); Victoria and Albert Museum, London (50); and the British Museum, London (10). Representative images spanning the early Christian era to the eighteenth century were sampled using micro-drilling techniques. These artefacts were analysed for the composition of eighteen major, minor and trace elements using simultaneous multi-element analysis by ICP-OES (i.e. inductively coupled plasma optical emission spectrometry) using equipment standardized by N. Walsh and N. Blades at Royal Holloway and Bedford New College, Egham.

In the most extensive application of lead isotope analysis to South Asian archaeology to date, 60 of the icons analysed by ICP-OES were also then subjected to lead isotope analysis using thermal ionisation mass spectrometry at Oxford Laboratory for History of Art and Archaeology using techniques standardized by Z. Stos and N. Gale. Lead isotope ratio analysis is a powerful method for archaeological finger-printing and classification because artefacts from similar sources of lead will have similar lead isotope ratios characteristic of the ore source. As discussed in Śrinivāsana,[98] it was found that from the lead isotope ratios and trace element profiles one could identify characteristic chemical 'finger-prints' for different stylistic groups of South Indian metal icons. Furthermore, the analytical signatures identified from chemical finger-printing for different stylistic groups of images could then be used to 'date' South Indian images; i.e. to make stylistic re-assessments for images of uncertain attributions. Thus, the sampled South Indian images were stylistically re-assessed and classified under the groups of Pre-Pallava, early Pallava and Andhra (c. 200–600), middle Pallava (c. 600–850) and later Pallava (c. 850–875), early and high Vijayalaya Chola period (c. 850–1070), early Chalukya-Chola (c. 1070–1125), later Chalukya-Chola (c. 1125–1279), later Pandya (c. 1279–1336), Vijayanagara and early Nayaka (c. 1336–1565) and later Nayaka and Maratha (c. 1565–1800).

From conventional art history based on visual comparison with stone sculpture, it had been believed that the Naṭarāja metal icon of the dance of Śiva with leg extended in the dance cadence of the *bhujaṅgatrasita karaṇa* was first developed by the powerful Śaivite Chola dynasty of Tanjavur, under whom metal and stone images of Naṭarāja were widely made. Unexpectedly then, the investigations undertaken by the author using lead isotope ratio analysis and trace element analysis suggested instead that the Naṭarāja bronze may have already been in vogue under the Pallavas who are known for the graceful stone sculpture at Mahabalipuram (c. sixteenth-eighteenth century) in Tamil Nadu.

Previously, there had been some debate amongst art historians about the attribution of bronzes to the Pallavas due to the lack of inscribed Pallava images. For example, noted art historian Douglas Barrett doubted whether there was a Pallava school of bronzes at all.[99] However, from the technical finger-printing exercise undertaken of lead isotope and trace element analysis the existence of a Pallava school of bronzes as distinct from Chola seems to be established. Indeed, two Naṭarāja images with the leg crossed in the *bhujangatrasita karana* better fitted technical trends for the Pallava group including the Kunniyur Naṭarāja from Government Museum, Chennai, and a Naṭarāja image from the British Museum (Figure 10.9). Thus, Naṭarāja metal icons were probably already cast by the Pallava and Later Pallava period (c. 800–875)

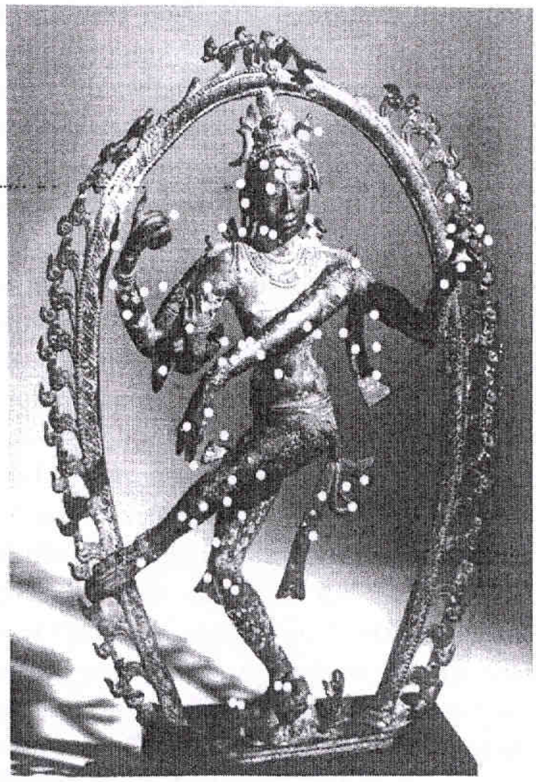

Figure. 10.9. Naṭarāja image with star chart of Orion, plotted by Nirupama Raghavan and attributed to the Pallava era by technical finger-printing by S. Śrinivāsan. Photograph of Naṭarāja courtesy of the trustees of the British Museum.

along with other depictions of Śiva's dance. The first clear stone Natarāja images seem to come into vogue at the Kailaśanāthaswamin temple built around 940 by the widowed Chola queen, Sembiyan Mahādevi, at the village named after her, whom Harle described as an all-time great patron.[100] That the casting of Natarāja bronzes flourished especially in the early Chola period is indicated by the fact that seven out of eleven sampled Natarāja images fitted trends for the Vijayalaya Chola group (c. 850–1070).

As such, evidence that the Natarāja metal icon may have been cast under the Pallavas had not come to light from art historical studies prior to the author's technical investigations as elucidated in Śrinivāsan.[101] However, although not easy to find, there is sculptural and literary evidence supporting the idea that the Natarāja bronze was developed under the Pallava dynasty. One of the earliest stone sculptures depicting Śiva dancing with the leg lifted in the *bhujaṅgatrasita karaṇa*, the dance movement associated with the Natarāja image, is found in a pilaster in seventeenth century Pallava cave temple at Siyamangalam in Tamil Nadu, although the left hand is not crossed over as in the typical Natarāja pose. The hymns of the Tamil Śaiva saint Appar suggest that by the seventeenth century the worship of Natarāja might have emerged at Chidambaram, the coastal shrine in Tamil Nadu, which is the only one where the Natarāja metal image is worshipped in the innermost sanctum or *garbha gṛha* instead of the aniconic pillar-like *liṅgam*. The local legend or *sthalapurāṇa* at Chidambaram describes the *ānandatāndava* or dance or bliss performed by Śiva at the forest of *tillai*.

There is some interesting evidence for astro-archaeological connections that may link the iconography of Natarāja to the constellation, Orion.[102] The present-day chariot processional festival of Margayi Tiruvadirai around the winter solstice at the Natarāja temple in Chidambaram is related to *ardra*, identified with a star in the constellation Orion, i.e., Betelgeuse.[103] Betelgeuse or Alpha Orion is a reddish super-giant star, and one of the brightest and largest.[104] In an collaborative study between the author and astro physicist Nirupama Raghavan, who has been exploring intriguing archaeo-astronomical connections, the star chart for the constellation Orion of 800 CE was mapped onto the Natarāja image from British Museum (Figure 10.9) identified by the author from archaeometallurgical studies as being of Pallava vintage. This superposition gave an amazingly good fit which not only suggests a likely 'stellar' inspiration for the Natarāja icon but also in a way perhaps ratifies the proposed dating of the image to the Pallava period. Thus, on technical and art historical grounds, the author postulates that the Natarāja metal icon emerged by the Pallava period, coeval with the rise of its worship at Chidambaram, and that the metal Natarāja icon preceded its stone representation.

In Manikkavachakar's mystical Tamil hymns to Natarāja (c. nineteenth century), he is variously evoked as the one consciousness (Oru Unarve), as the five elements including ether (or *ākāśa* in Sanskrit) in the verse below, and as the cosmic dancer.

> Ah, When will I get to gaze upon the unique
> One to whom no other compares

Him who is fire, water, wind, earth and ether,
Him whom others cannot understand...

Another of Manikkavachakar's verse goes 'let us praise the Dancer (*kuttan*) who in good Tillai's hall (i.e., Chidambaram) dances with fire, who sports (*vilaiyatu*), creating, destroying, this heaven and earth and all else.'[105]

The rich symbolism of the existing twelfth century temple complex of Chidambaram (*cit*: consciousness; *ambaram*: cosmos) seems to celebrate Śiva as not only the cosmic dancer but also the cosmic consciousness. Here, in the *cit sabhā* or hall of consciousness, Śiva is worshipped both as the *ākāśa liṅgam,* or the element sky symbolized by empty space, and as the metal Natarāja icon. On the outer *gopuras* or temple towers are sculpted the one hundred and eight *karanas* or cadences of Śiva's dance. It is thus tempting to perceive in the symbolism something of the basic rudiments, or at least a post-modernist metaphor, of concepts that have only more recently been grappled with in modern physics, such as mass–energy equivalence, or notions such as put forth by mathematician Roger Penrose for a possible grand unified theory of the forces of the universe, encompassing quantum consciousness. According to Upaniṣadic concepts, *ākāśa* or ether is one of the five elements of the cosmic principle or *Brahman,* apart from earth, water, wind and fire.

Neuro scientist Ramachandran found in the Chola bronzes of the goddess Parvati a means to explain concepts in neuro-aesthetics with regard to why we respond to these bronzes: by evoking the peak shift principle 'whereby feminine sensuality is conveyed by subtracting the male average form from the female average form and then amplifying the difference.'[106]

Wootz Steel

As pointed out in a book by Śrinivāsan and Ranganathan,[107] in antiquity, India had been a world leader in producing high-grade steel several hundred centuries before comparable steel came into vogue in the West. European travellers in the seventeenth century observed cakes of steel being made by crucible procesṣes in southern India in Andhra Pradesh, Karnataka and Tamil Nadu, known in local languages of the region as '*ukku*' which they termed 'wootz'. The novelty of 'wootz' lies in the fact that it was a high carbon steel with 1–1.5 per cent carbon; whereas in Europe only low-carbon steels (i.e., with not more than 0.6–0.8 per cent carbon) had been in vogue.

Indian wootz steel was especially sought after across the oceans in Persia and the Arab world to make a naturally wavy-patterned sword blade: the fabled Damascus blade that was encountered by the Christian West in the Islamic Middle East during the Crusades (c. twelfth–fourteenth centuries). The beautiful patterns on such blades were a result of processes of forging and etching the high-carbon steel wootz ingot: with the darkly etched pearlitic phase alternating with the lighter, higher carbon cementite phase. Perhaps no materials of antiquity have been as feted in literature, historical accounts, films, and in recent times, the Internet as wootz, with its synonymous terms of Damascus steel, Bulat, (the Russian term derived from the Persian term *poulad*, for wootz) and Ondanique, derived from the Arab term 'Hinduwani' meaning Indian steel; attracting the attention of writers of the repute of Walter Scott and Alexander Pushkin.[108]

Experimental reconstructions by Wadsworth and Sherby in the 1980s have demonstrated that ultra-high carbon steels with about 1.5 per cent carbon exhibit fascinating superplastic properties. Superplasticity is a remarkable phenomenon that allows a material to change its external shape to a very great extent without changing within. Wootz was thus an 'advanced material' of the ancient world used in three continents for well over a millennium. Neither its geographic sway nor its historic dominance is likely to be equalled even by the advanced materials of our era.

Ukku seems particularly similar to the old Tamil words *ekku*, used to describe spears or sharp edges, and *urukku*, meaning oozing or melting, which is close to a description of the crucible process. The words *ekku* and *urukku* are also found in classic Tamil Sangam literature of the fifth-century BCE to fifth century CE, the oldest corpus of poetry in Dravidian languages. The moving bardic Tamil poems of the remarkable poetess Auvaiyar are particularly evocative of the skirmishes with spears between rival chieftains of that era. Indeed, there is a mention in early excavation reports of two javelins with 1–2 per cent carbon from megalithic sites in Andhra Pradesh in southern India.[109] Investigations by the author on crucibles from the site of Mel-siruvalur showed the metallic remnants (Figure 10.10) to be of high-carbon wootz steel.[110] Investigations by the author on a crucible fragment from the megalithic site of Kodumanal, Tamil Nadu (third century BCE), excavated by K. Rajan, Tamil University, uncovered in an iron smelting hearth showed it to be iron-rich (Śrinivāsan and Griffiths 1997).[111] Sasisekaran reports a chisel from Kodumanal with 0.9 per cent carbon.[112] If one were

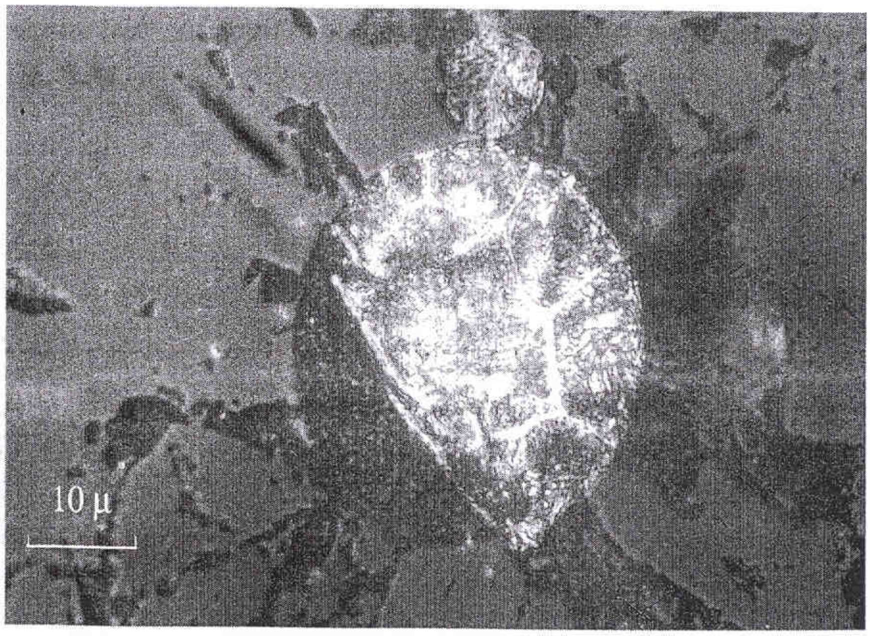

Figure 10.10. Micro structure of high-carbon wootz steel remnant from crucibles from Mel-siruvalur.

to accept that the origins of *ukku* steel lay in the Sangam domain, then it is noteworthy that there is also an aesthetic or 'lettered' aspect (at least in the manner of oral literacy) to this culture as signified by the excellence of the poetry.

Accounts of the Greek Zosimos of the early Christian era suggest that the Indians used crucible processes to make metal for swords, i.e. steel[113] while Pliny's *Natural History* talks of iron from the Seres, which might refer to the ancient South Indian kingdom of the Cheras mentioned in Sangam texts.[114] Literary accounts suggest that steel from the southern part of the Indian subcontinent was exported to Europe, China, the Arab world and the Middle East. In the twelfth century the Arab Idrisi commented that 'The Hindus excel in the manufacture of iron. It is impossible to find anything to surpass the edge from Indian steel.'[115] The links between aesthetics and high science is also demonstrated by the highly poetic Arabic accounts of the patterns on the Damascus blades that they were also masters of generating. These patterns were perhaps also greatly venerated due to the near calligraphic quality, which is one of the highest arts in Islam, transmitting as it did the word of the Quran.

Accounts from the Middle East from the Middle Ages suggest that this steel of Indian origin, which was used to make Damascus swords, was known as *Poulad*, which later came to be known as *bulat* in Russia by the eighteenth-nineteenth century, with the interest of Russian metallurgists such as Anacoff, who seems to have been the first to replicate wootz or Damascus steel in Europe. Bulat almost acquired an iconic status in Russia through the writings of high-profile people such as Anacoff and the celebrated Russian writer Pushkin.

Wootz steel also played an important role in the development of metallurgy, as elucidated by Cyril Stanley Smith.[116] Michael Faraday, the greatest experimenter of all time, tried to duplicate the steel by alloying iron with a variety of metallic additions including noble metals, but failed. As he was the son of a blacksmith the extraordinary properties of wootz steel must have fascinated him. His failure had an unexpected and fortunate outcome as it marked the beginning of alloy steel making.

Aranmula Delta High-Tin Bronze Mirrors

An extraordinary surviving traditional high-tin bronze craft is the making of 'delta' high-tin bronze mirrors in Aranmula village in Kerala. The author's technical investigations[117] first established that the Aranmula mirrors (Figure 10.11) were made of an alloy that can be described as a high-tin delta bronze, i.e., 33 per cent tin-bronze (Figure 10.12), so-called because of the match with the composition of pure delta phase, an intermetallic compound ($Cu_{31}Sn_8$) of 32.6 per cent tin; whereby the mirror-effect was obtained by optimizing its presence. The predominance of delta phase yields an ideal mirror material as it is a very hard and stable compound that can hence be polished with the best possible mirror effect, free of distortion, with reflectance across the entire spectrum. Its brittleness is offset by casting a very thin blank in a two-piece crucible-cum-mould.[118] In a forthcoming article for the *Encyclopeadia of Non-Western Science* by the author it is shown that an old mirror had a structure of almost pure delta crystals as agreed by Tom Chase, renowned expert on ancient bronzes. A mirror sample

Figure 10.11. Mirror of high-tin delta bronze from Aranmula, Kerala.

from the Nilgiri cairns studied by Breeks[119] had 30 per cent tin, while a sample from Sonepur in eastern India (c. 500 BCE–500 CE) reportedly has 32.4 per cent tin, which matches the delta bronze composition of the mirror alloy.[120] Hence the exceptional and early exploitation of the properties of intermetallic compounds of bronze is indicated in the Indian subcontinent and southern India.

The manufacture of the Aranmula Kannadi has been a zealously guarded secret of all but a handful of surviving master craftsmen known as *acharis*, and discussions

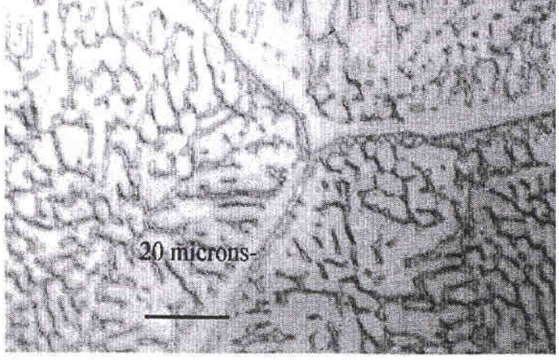

Figure 10.12. Micro structure of above high-tin delta bronze mirror with 32–33 per cent tin close to the composition of pure delta phase.

with them indicate that they believe the craft has an indigenous origin. Local legends link the history of the Aranmula mirror to the Parthasarathy temple to Krishna at Aranmula, one of Kerala's five most sacred shrines. One lively story of the origins of the Aranmula metal mirror was reported in 1992 to Ian Glover by mirror maker Janardhanan Achari.[121] The Rājā of Aranmula had threatened to evict some bronze craftsmen, who are said to have originally migrated from Tamil Nadu to make artefacts for the Parthasarthy temple, since they had grown fat and lazy. A widow, Parvati Ammal, came to their rescue when she dreamt that Lord Parthasarthy or Krishna had revealed the secret of making an unusual reflecting metal. In an interesting twist, not only was the king placated by the crown made of this material but he also exhorted the artisans to make mirrors for the auspicious *aṣṭamaṅgalyam* wedding sets of brides-to-be from this alloy dreamt up by the widow. This is an interesting instance of how the aesthetic-ritual milieu and pressure from the royal patron may have motivated the use of this alloy rather than purely functional aspects.

COLONIAL TRANSFERS OF INDIAN TECHNOLOGY TO EUROPE: WOOTZ STEEL AND ZINC

In the eighteenth and nineteenth centuries the European forays and colonial expansions into the east resulted in several previously unknown eastern techniques and technologies coming to light and being intensely studied and 'invented', or more truthfully reinvented but on a much larger and often even epoch-making scale. This process included several Indian technologies, apart from Chinese or West Asian. As mentioned before, Smith has discussed how Oriental textures inspired European science.[122]

One of the interesting examples of a possible transfer of technology concerns the rockets made by the flamboyant late eighteenth century ruler of Mysore, Tipu Sultan. To quote Darius et al.,

> in India in the sixteenth century armies carried thousands of rockets into battle. British troops captured some examples in 1799 and took them to the Woolwich Arsenal near London for study ... The Indian rockets may have inspired the British inventor Sir William Congreve, who turned the black powder rocket into a 'weapons system' during the Napoleonic Wars.[123]

The historiography of studies made on wootz provides a fascinating record of how an eastern material played a pivotal role in spurring many discoveries related to modern metallurgy and science. It also gives fascinating insights into not just a transfer but also transformation of a technology that took place in not just overt but also covert ways. Hence the Indian wootz steel deserves a special place in discussions related to the foundations of science.

The characterization of wootz and Damascus steel was one of the motivating forces in the development of metallurgical science and the study of micro-structures in the eighteenth and nineteenth centuries. Although iron and steel had been used for thousands of years, the role of carbon in steel as the dominant element was found only in 1774 by Tobeck Borgman due to European efforts to unravel the mysteries of wootz steel and true and patterned/textured Damascus steel. Similarly the textured Damascus steel was one of the earliest materials to be examined under the microscope. British, French and Russian metallography developed largely due to the quest to document this structure. However, it is perhaps ironic that in modern text books, Indian wootz steel does not get so much as a passing mention in a historical context (unlike Chinese cast iron) although the names associated with such studies of Michael Faraday, David Mushet, Robert Hadfield and others rank amongst the all-time greats of early metallurgy.

An interesting insight into how wootz was one of those eastern materials that, behind the scenes, spurred numerous patents invented in nineteenth century Europe comes from an account related to David Mushet. David Mushet is one of the well-known early nineteenth century metallurgists who took an interest in reports of the manufacture of wootz steel by the so-called Deccan process by a few families in the region of Tiruvannamalai in Tamil Nadu. The steel makers in the Tiruvannamalai region are said to have made grey cast iron in small blast furnaces, following which it was fired in the crucibles along with low-carbon 'malleable iron'. The process of co-fusion was one where a higher carbon cast iron was mixed with low carbon wrought iron to get a steel of intermediate high-carbon composition. In 1800 David Mushet brought out a patent on a crucible steel process and by 1805 he had made his report to the Royal Society in which he was able to infer that wootz/crucible steel was made by a fusion process, i.e., not solid state cementation. He attributed the patterns related to crystallisation observed at the rounded base of the steel ingot to the 'want of homogeneity and solidity' and of the carbon context which approached 'very near to the nature of cast iron.'[124] Indeed, Percy's writings go so far as to pointedly hint that Mushet's patent was borrowed or inspired by the Indian wootz processes. He says,

> It is curious that Mushet's process, so far as related to the use of malleable iron in the production of cast-steel, should in principle, and I may add even in practice too, be identical with that by which the Hindus have from ancient times prepared their wootz. I cannot discover any essential difference between the two.[125]

The advent of the British colonizers saw the terminal decline of this great indigenous steel-making tradition of India by the 1850s. Thereafter, although new technologies of iron and steel making were being developed during the Industrial Revolution in Britain and Europe, such as the use of coke for mass production, these mainline developments in steel technology did not take place in India.

One of the interesting questions in history of science is the 'Needham paradox', which is that although when China before the eighteenth century was one of the most scientifically advanced civilizations, it was not there that the Industrial Revolution took place but in Europe. In the light of some of the metallurgical inventions mentioned above from the Indian subcontinent, the question may be raised as to why, when clearly studies on Indian wootz and Damascus steel stimulated several developments in iron and steel metallurgy that were at the core of the Industrial Revolution, development within India itself had stagnated. In India craftsmanship and artisanship in the pre-industrial era had reached great heights, whereby artefacts were handcrafted, requiring considerable technical skill, and processes were even carefully and precisely replicated as seen in the case of wootz steel. These skills were finely honed partly due to the specialization of crafts/cottage industries brought about by division of labour by caste and other factors such as the existence of craft guilds. However, the disconnect between the artisan class and the educated elite or the priestly upper caste, who generally had the monopoly of textual knowledge may have been detrimental to the development of the science behind these empirical activities. This may have resulted in constraints on the former's ability to experiment and most especially to record experiments, which is so essential to scientific methodology. Furthermore, as seen in the case of the Aranmula mirror mentioned before, the craftsmen's motivations were often restricted to the needs of the ruling patron, which were mainly ritualistic or elitist in nature.

In marked contrast, perhaps even with the situation in China, a spirit of directly working with one's hands and experimentation with a sense of individuality seems to have marked the European enterprise in the seventeenth and nineteenth centuries. Michael Faraday, the inventor of electricity and one of the greatest of experimenters to conductor experiments on wootz steel, had the sort of background that epitomizes a balance of the practical and the erudite; he was the son of a blacksmith and spent his early education baried with books.

In England, crucible steel first came into vogue in 1740 through Britisher Benjamin Huntsman with a major practical application being for clock springs and, given the interest in Indian crucible steel processes mentioned, there is a possibility of some borrowings of these ideas. Thereafter, it did take about a half a century for European crucible steel to catch on with the watchmakers.[126] On the other hand, in India itself where crucible steel had been in vogue for so many centuries longer, it is interesting that, the evidence for spring steel in a traditional context comes from the exotic, flexible, deadly urumi blades (Figure 10.13) used in combat in the Kalaripayattu martial

Figure 10.13. Flexible *urumi* blades in the Kalaripayattu martial art tradition of Kerala which S. Śrinivāsana's studies showed were made of spring steel.

art form, as the author's scientific studies confirmed.[127] However, the use of this spring steel in the Indian context seems again circumscribed by the ritual–aesthetic–performance art domain and never went on to develop into any practical application.

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