PROCEEDINGS OF SCIENCE

Contribution of astronomy to art conservation and archaeology

Haida Liang[1]
School of Science and Technology, Nottingham Trent University
Clifton Lane, Nottingham NG11 8NS, UK
E-mail: `haida.liang@ntu.ac.uk`

The application of physics to art history, art conservation and archaeology is currently a growing area of research. Astronomy and astrophysics have made significant contributions to imaging science which has in turn contributed to the developments of many other fields ranging from biological science to the study of art history, archaeology and art conservation. This paper will discuss how knowledge traditionally associated with astrophysics have made impact on the study of cultural heritage. Examples will be drawn from recent research carried out in my research group.

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[1] Speaker

1. Introduction

This workshop is held at the same time as the exhibition of the *THE ANTIKYTHERA SHIPWRECK - The ship - the treasures - the Mechanism* at the National Archaeological Museum of Athens. One not so obvious connection between astronomy and the Antikythera mechanism is that research in astronomy has contributed to the study of art history, archaeology and art conservation through the non-invasive imaging techniques and various other knowledge developed in astronomy research in the last 100 years. Astronomy is both a fundamental and an applied research discipline. Historically astronomy paved the way for the development of physics, but it in turn became a kind of applied physics, that is physics applied to the understanding of the universe.

Conservation science, that is science applied to art conservation, is about as old as Radio Astronomy. In 1815 Sir Humphrey Davy and his then assistant Michael Faraday travelled around Europe to study ancient Greek and Roman pigments from wall paintings and other artefacts [1]. In 1830 the British Museum consulted Faraday on the application of a wash to prevent the deterioration of the surface of the Elgin Marble from the effect of pollution [2]. In 1850 and 1853 two House of Commons Select Committees were appointed to investigate the safety of the methods used by the National Gallery (London) to clean off old varnish on oil paintings and the effect of air pollution on the old master paintings. Michael Faraday was called upon by museums at various times to give advice and he carried out experiments on the application of alcohol to clean old yellowed varnish off paintings as well as analytical studies on the effect of smog on the discoloration of painting surfaces and that of the Elgin Marbles [3]. It was not until the 1930s that a number of major European and US museums had scientific laboratories and advisors and thus opening up a new discipline of conservation science. Infrared and X-ray photography were already employed to examine paintings and artifacts to reveal features invisible to the naked eye. At the beginning, many of the scientists working in these museums were physicists but as micro-chemical analysis became increasingly effective, chemists took over. However, owing to the recent developments in imaging science (partly due to the much reduced costs of detectors such as CCDs and the needs in biomedical imaging), physicists are once again making an impact in this field.

The application of physics, in particular optics, imaging and material science to cultural heritage is an emerging field that is growing. A brief glance at two international conferences series: LACONA (Lasers in the Conservation of Artworks) and SPIE conference O3A: Optics for Arts, Architecture, and Archaeology shows increasing activity and range of topics.

It is perhaps surprising how astronomy can have an impact on seemingly unconnected disciplines such as art conservation and archaeology. Since I have worked in astrophysics and in heritage science (i.e. the application of science to art history, archaeology and art conservation), specifically application of physics to archaeology and art conservation, I will give some examples through my own experience.

2. Imaging in Astronomy is non-invasive

It is well known that astronomical imaging techniques have many similarities with biomedical imaging. The same connections can be found with imaging of historical objects. Imaging in astronomy is necessarily non-invasive given the vast distances. We would like to perform invasive probing of galaxies but we cannot. On the other hand, historical objects are fragile and non-invasive techniques are preferred and in some cases the only possible method.

2.1 From Michelson interferometer to Optical Coherence Tomography (OCT)

Michelson invented the Michelson interferometer in 1881 to detect ether in the Michelson-Morley experiment [4] and invented the stellar interferometer in 1890 to measure the size of Jupiter' satellites [5]. Later interferometers in the optical and the radio including the SKA are descendants of the Michelson stellar interferometer. While we now know that light does not need a medium to propagate, the concept of a medium that permeates the entire universe is still there in the form of intergalactic media. The Michelson interferometer has lasting impact on many branches of science since it can be used for precision spectroscopy in the form of Fourier-transform spectroscopy such as the Fourier Transform Infrared (FTIR) spectroscopy and for precision metrology when one of the mirrors is replaced by the sample. In 1991, the Michelson interferometer was turned into a fast subsurface imaging device for the non-contact *in vivo* imaging of the eye and given the name Optical Coherence Tomography (OCT) [6]. This is made possible by the developments of broadband laser sources and optical fibres in the telecommunication industry as well as faster electronics and computing technologies. The depth resolution of OCT increases with the bandwidth of the source. There are broadly two types of OCT: 1) time domain OCT where the reference mirror scans to produce the fringes and the centre of a fringe envelope gives the depth position in the sample from where the light has scattered back; 2) Fourier domain OCT where the reference mirror is fixed but the interference signal is either dispersed through a spectrograph or scanned in wavelength using a tuneable laser to reveal the fringe pattern which is then Fourier transformed to obtain the depth profile. Fast scanning mirrors are used to scan the incident beam across the sample to form 2D or 3D tomographic images. There are many analogies between Fourier domain OCT, where the data is collected in the Fourier domain, and radio synthesis arrays such as the SKA. The need for better resolution of OCT images has led to the application of various deconvolution methods developed in astronomy. These include the CLEAN algorithm [7], the maximum entropy method [8] and the Lucy-Richardson deconvolution [9].

Recently, OCT has been applied to the non-contact imaging of the layer structures of paintings and other historical objects [10][11]. Figure 1 shows a 930nm OCT image of a painting where the cross-section image shows varnish and paint layers and underdrawings. The slice extracted at some depth parallel to the paint surface revealed the drawings under the paint layers. OCT is not only useful for non-invasive tomographic imaging (i.e. subsurface volume imaging), it can also be used for precision profilometry (i.e. measure of the surface profile) up to a precision of 50nm [12]. There is potential for OCT to be applied to the Antikythera mechanism to reveal carved inscriptions on the surface. Figure 2 shows an example of OCT used to reveal the tiny Chinese inscriptions on a piece of jade. The characters were carved on to the jade and ink was then applied.

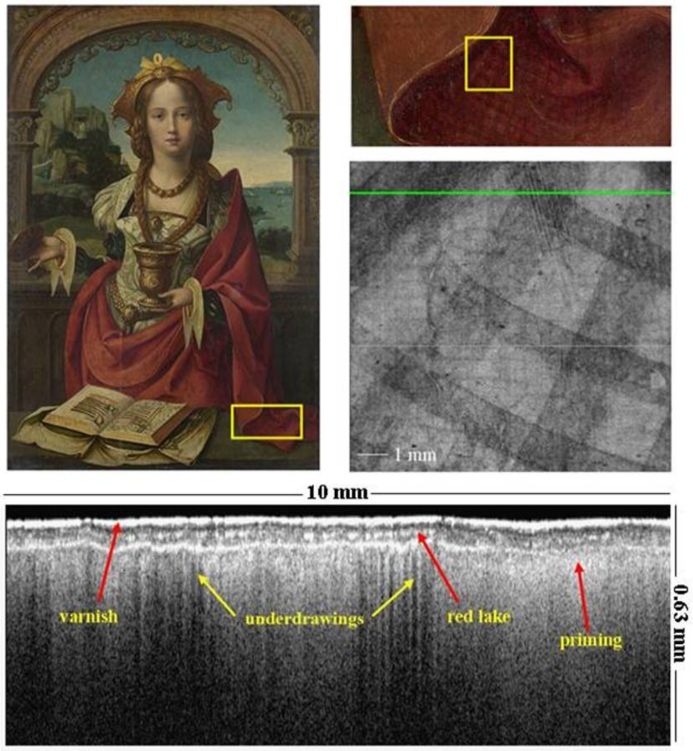

Figure 1: Top left: The Magdalen by an anonymous Netherlandish artist (NG719 © National Gallery); Top right: a region of the red drapery marked by the box on the full picture; Right middle: OCT (930nm) image at the depth of the underdrawing corresponding to the region marked by a yellow box in the top right image. Bottom: OCT cross-section image of the region marked by a green line segment [10].

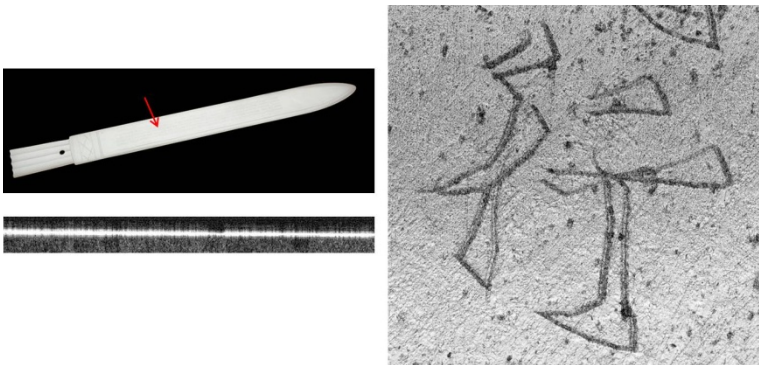

Figure 2: Left top: A jade Ge with fine characters inscribed (BM1945,1017.135, © Trustees of the British Museum); Left bottom: OCT cross-section image around the jade surface marked by the red arrow above (image size: 3mm wide by 0.19mm depth); Right: OCT image averaged from 30 slices in the image cube above and below the jade surface (image size: 3mm by 3mm).

2.2 All sky multi-band photometry for cave paintings

Multispectral and hyperspectral imaging are spectral imaging techniques well known in remote sensing. Multi-band photometry is perhaps a more familiar term to astronomers. Essentially a filtering system is employed to image an object in various optical spectral bands and spectral data is efficiently obtained for the entire field of view at the expense of reduced spectral resolution compared with spectroscopy. An analogy is the well-known trade-off between photometric redshift and spectroscopic redshift in astronomy.

Multispectral imaging started to be used for imaging paintings in the 1990s first as a means of improving the accuracy at recording the colour of paintings (using 6-7 bands) and later in recovering the spectral reflectance of the paint (using 10-13 bands from 400nm to 1000nm) for pigment identification since pigments have their characteristic reflectance spectra [13]. The difference from astronomy is that reflected rather than emitted light is collected. Currently a number of major museums in the world have multispectral imaging devices in their studios. However, large scale imaging of wall paintings in buildings and caves was still inconvenient and high resolution imaging of paintings at lofty heights were not possible with a normal camera system unless it was lifted close to the painting. It is interesting that the idea of remote imaging was forgotten once multispectral imaging was moved to a gallery studio even though the technique was originally borrowed from remote sensing. As an astronomer, remote imaging using a telescope seemed the obvious thing to do in the case of wall paintings. Consequently, we developed a system called Portable Remote Imaging System for Multispectral Scanning (PRISMS) for in situ high resolution imaging of wall paintings. It is fully automated with a small amateur astronomy telescope with its own drives, filtering system and CCD camera. The application of the PRISMS system was best demonstrated at the UNESCO world heritage site of Mogao caves in Dunhuang on the edge of the Gobi desert along the Silk Road. The site has nearly 500 painted Buddhist cave temples. Scanning of an entire cave is similar to an all sky multi-band photometric survey since the caves are painted ceiling to wall. However, in this case we needed another telescope to project the source of illumination so that enough light can be reflected from distances > 10m. The imaging system including the light stays at one position throughout the survey just like a normal telescope. Perhaps not surprisingly ‘cave seeing’ was found to be a limiting factor to the resolution. The images are automatically mosaicked together in post-processing using cross-correlation to find the relative position shifts between neighbouring images. The spectral image cube can also be converted into colour images for a given light spectrum. The images in the near infrared bands revealed preparatory drawings under the paint layers since paint is more transparent in the near infrared. Image processing of the images in various spectral bands can reveal faded writings which can assist in revealing the history of the paintings. Spectral reflectance for various paints can be compared with those with known pigments to identify the pigments. All these are done remotely without the need for scaffolding. Figure 3 shows PRISMS scanning a cave in Dunhuang.

Figure 3: The spectral imaging system PRISMS in cave 465 of Mogao caves, Dunhuang. The imaging system is on the left of the lighting system.

3. Radiative transfer theory – from stellar atmosphere to paintings

When I first looked into how to predict the reflectance spectrum of a paint mixture of different pigments using known reflectance spectra of single pigment based paints, references to Schuster's 1905 paper [14][15] on radiation transport in a stellar atmosphere came up frequently. Schuster assumed that the medium uniformly emits, absorbs and scatters light. Differential equations were written for fluxes in two opposite directions in a thin slice of the medium. Absorption and scattering reduces the intensity of a beam, but back-scattering of the beam in the opposite direction increases the intensity. He assumed Rayleigh scattering and that one half of the light is scattering in the forward direction and the other half in the backward direction.

The commonly used model in the textile and paint industry is the Kubelka-Munk (KM) theory first presented in 1931 [16]. It is a special case of Schuster's model for a diffusely illuminated homogeneous medium that only absorbs and scatters but does not emit light. However, Kubelka and Munk did not seem to be aware of Schuster's paper as they didn't refer to it. Today Schuster's paper of 1905 [14], Chandrasekhar's book of 1950 [17] and van der Hulst's thesis of 1957 [18] are acknowledged as the basis to predicting colour of paint mixtures, colour matching in textile dying and modelling light scattering in turbid medium which includes light transport in biological tissue [19][20]. Schuster's and therefore the KM models are approximations of the radiative transfer models. KM model is by far the most widely used because of the simplicity. Radiative transfer models are difficult to solve analytically. The KM model gives accurate results for diffuse illumination of matt weakly absorbing but optically thick media (i.e. scattering is significant). The assumption of diffuse illumination in KM model cannot be true in the presence of strong absorption because absorption is larger for more oblique rays and hence absorption acts to collimate the light. Schuster pointed out this limitation in his own model. In addition, most pigments are in the size range for Mie scattering which favours forward scattering. Currently for pigment identification from spectral measurements of a paint that is likely to be a mixture of pigments, KM theory or Schuster's model appears to work well when at least one of the pigments in the mixture scatter light significantly in the wavelength range of interest [13]. In cases where it fails, more complex numerical solutions to radiative transfer theory have to be used.

4. Reciprocity law – from photometry to photo-degradation

Photographic plates were the first detectors used for imaging and photometry. Reciprocity law was used to describe the reciprocal relation between intensity and exposure time in producing the same optical density on a film. In other words, reciprocity law states that photo-degradation is independent of the intensity of the incident radiation and only dependent on the total incident energy. Photometry requires a calibration between incident energy and the resultant optical density of the photographic material. However, such a calibration usually assumed the reciprocity law between intensity and exposure time. Karl Schwarzschild's 1909 paper [21] on reciprocity law failure applied to stellar photometry using photographic plates is one of the often quoted papers in the degradation of photographic plates and other objects. Schwarzschild found that under low light conditions applicable to astronomy where exposure times are measured in minutes or hours, the reciprocal relation between intensity (I) and exposure time (t) no longer held and instead a new relation of $It^p = constant$ where $p = 0.86$ fitted the data better. The relation is these days commonly referred to in the photographic industry as Schwarzschild's law and p is referred to as the Schwarzschild coefficient [22]. It is well known that light can induce chemical reactions in materials. Such a process is behind the basic principle of photography but is also an undesirable effect of light on works of art (including photographs). Accelerated ageing is a process where a material is subjected to irradiation by a strong light source (often orders of magnitudes more intense than the intended lighting level), so as to estimate the vulnerability of a material to photo-degradation over an extended period of time. This would only work if reciprocity principle holds or if we can find an equivalent Schwarzschild's law for a material.

5. Conclusions

Astronomy has unexpectedly made impact in a number of seemingly unrelated fields. From my personal experience, I have found the above areas of astronomy that is of relevance to the study of art history, archaeology and art conservation. Modern imaging techniques such as OCT which was derived from instruments originally made for answering astronomical questions may in turn be used for deciphering a long lost ancient astronomical instrument - the Antikythera mechanism.

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