Techniques in X-ray Astronomy

1. Imaging Telescopes

Kulinder Pal Singh

X-ray astronomy has benefited enormously with the deployment of imaging X-ray telescopes in space, leading to a veritable revolution. Such telescopes require distortion free focusing of X-rays and the use of position sensitive X-ray detectors. In this article I shall describe the importance of X-ray imaging, the optical principles behind the creation of images and the instruments based on these principles. The various techniques used to fabricate such X-ray telescopes are described briefly. The many types of detectors used in X-ray astronomy will be described in the second part of this article in a subsequent issue of *Resonance*.

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Introduction

X-ray astronomy is a major branch of astronomy spanning 10 octaves of the electromagnetic spectrum (0.1 Angstroms to 100 Angstroms, or 100 eV to 100 keV), compared to a single octave accessible to optical astronomers. Today, X-ray observations are central to the study of almost all kinds of cosmic objects: stars, galaxies and quasars. X-rays originate in, and thus probe: (a) the hottest plasmas in the farthest reaches of the universe; (b) the most energetic events and shocks produced by such events as distant supernova explosions; (c) very high electric and magnetic fields that can accelerate electrons to very high energies releasing X-ray photons; and (d) the release of gravitational energy due to in-fall of matter on highly compact objects such as white dwarfs, neutron stars or 'black holes'. The fact that X-rays can excite and ionize atoms implies that X-rays emitted or absorbed by an atom of a particular element give a fingerprint for the energy states of that atom. This knowledge, or energy spectrum, helps astronomers to look for and determine the

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amount of each element present in the source of X-rays or in the matter interspersed in the intervening space in the direction of the source.

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The development of X-ray astronomy is tied up with the development of rockets and satellites that are required for carrying X-ray telescopes and detectors above the absorbing layers of the Earth's atmosphere. Beginning with simple detectors in 1962, equivalent to a naked eye in visible astronomy, the X-ray instruments today are a billion times more sensitive rivaling the capability of 8 to 10 metre class of optical telescopes. These developments have led to observations of X-rays from planets to the distant clusters of galaxies and quasars.

The cosmic sources of X-rays are usually very weak. Detection of these sources in the harsh environment of space is normally done on a photon-by-photon basis against a very strong background. The earliest instruments used for X-ray astronomy were simple gas filled proportional counters used in nuclear physics in which X-rays are detected by photo-ionization of the gas. The sensitivity of these instruments was dependent on the area of the detectors, the absorption cross-section of the gas, and the techniques used for the reduction of non X-ray background. Techniques like shielding, mechanical collimation, and anti-coincidence with neighbouring cells or rise time discrimination of the charge pulse produced by an X-ray photon or a charged particle are used to reduce the unwanted background. Large areas meant uniformity of response that was created by having multiple cells of small size with uniform electric field defined by a large number of anode and cathode wires. X-ray proportional counters are the workhorses of X-ray astronomy covering nearly the entire energy range of X-rays. This approach is quite adequate for bright X-ray sources, and can still lead to major scientific advances (as in the *Rossi X-Ray Timing Explorer (RXTE)* launched by NASA in 1996). Earlier examples of X-ray satellites based on such detectors are: *High Energy Astronomical Observatory –1* in 1977 by NASA, *Ariel-V(1975, UK), European X-ray Observatory SATelite (1983, ESA), Tenma (1983, Japan), Ginga (1987)* observatory of Japan and UK, and *Indian X-ray Astronomy Experiment* on Indian Remote Sensing satellite – P3 (1996). A multi-wavelength satellite called *ASTROSAT* being built in India will carry three large area xenon gas filled proportional counters.

There are, however, practical limitations on increasing the areas of the proportional counters and on making very fine collimators with highly restricted field of view. Thus, it is very difficult to detect many thousands of weak X-ray sources that comprise the background as seen by proportional counters with a collimated field of view. A combination of an X-ray telescope that can concentrate the X-rays on to an imaging X-ray detector can enhance the sensitivity manifold, help us view several X-ray emitting objects simultaneously, and can even create pictures of regions from where diffuse X-ray emission arises.

X-rays reflect from a surface up to a critical angle given by cosine $\theta = n$. This is known as the *grazing angle*.

Imaging X-ray Telescopes

To make an X-ray telescope we need to be able to reflect and focus X-rays. Conventional refracting or reflective optics is impractical because the refractive index for X-rays is less than unity and single surface reflectivity for near-normal incidence is negligible. X-ray photon energies are greater than the binding energies of the typical atomic electrons leading to an index of refraction, $n < 1$ except near absorption edges of the material used. Then by Snell's Laws, total external reflection occurs and X-rays reflect from a surface up to a critical angle given by cosine $\theta = n$. This is known as the *grazing angle*. If n is expressed as $1-\delta$, then $\theta = (2\delta)^{1/2}$ where $\delta = N_0 Z r_e \rho\lambda^2/A\, 2\pi$. For heavy elements, Z/A is about 0.5, and $\theta = 5.6\, \lambda\rho^{1/2}$ arcmin (where λ is in Angstroms, and ρ is in gm/cm^3), θ is proportional to $\rho^{1/2}/E$ where E is the photon energy. Ni, Au, Pt, and Ir are good reflectors and are used for making X-ray mirrors. The value of critical angle is typically in the range of 10 arcmins to 2 degrees for the energy range of 0.1 to 10 keV for surfaces of Au, Ni, Pt or Ir coated on substrates of glass, Al, reinforced carbon-fibre, and most recently plastics. Fresnel's equations give the functional form of the reflection curves.

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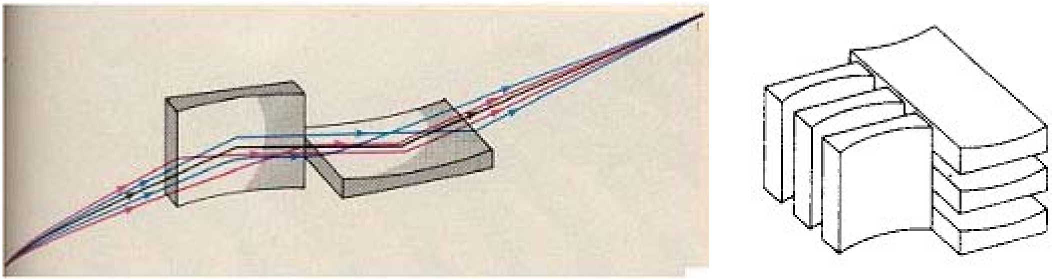


Figure 1. Kirkpatrick-Baez optics (left) and stacking of parabolic sheets (right) to increase the effective area of reflection.

Credits: Underwood, J H and Attwood, D T in Physics Today (1984).

A parallel beam incident at a grazing angle on a curved parabolic plate will focus in 1-dimension to a line, leading to severe astigmatism. Therefore the first 2-dimensional X-ray images in the laboratory were made in 1948 using 2 sets of parabolic sheet mirrors (parabolas of translation) with axes of revolution perpendicular to each other. Here, light emerging from the front mirror was intercepted by the rear mirror (*Figure* 1). A spatial resolution of 5-10 arcsecs for on-axis, and 1 arcmin for X-rays one degree off-axis, was achieved. This kind of optics is known as the 'Kirkpatrick-Baez optics'.

In two remarkable papers in 1952, H Wolter described a series of designs and geometries for such X-ray telescopes. The one most commonly used consists of a set of co-axial and con-focal shells of paraboloidal and hyperboloidal mirrors. X-rays are first reflected by an internally reflecting paraboloidal mirror and then reflected to the prime focus of the telescope by the internally reflecting hyperboloid mirror (*Figure* 2). Focal length is measured from the mid point of the paraboloid and the hyperboloid. At grazing incidence, the active region of the mirror is just a thin annulus giving a small collecting area even for a large diameter mirror. Therefore, several Wolter I shells are nested to improve the filling factor of the circle defined by the outermost shell, and thus increase the reflecting areas. Telescopes for soft X-rays in the energy range of 0.1–10 keV have been built based on this geometry and have provided X-ray images with arcsec to sub-arcsec resolution that have revolutionized X-ray astronomy. The mirrors in each of these observatories were figured to perfect paraboloid and hyperboloid shapes by diamond turning

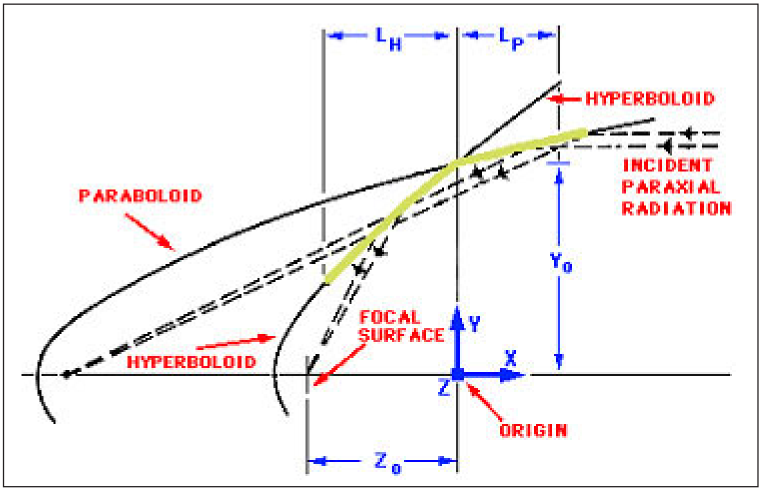
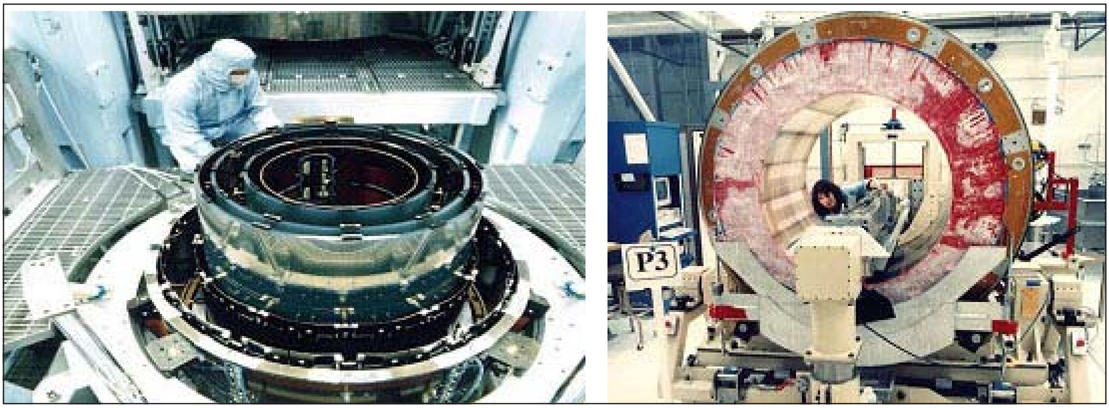


Figure 2. A Wolter type I telescope consisting of co-axial and con-focal paraboloid and hyperboloid. This geometry was used in the Einstein(NASA), ROentgenSAT (Germany, USA, UK), and the Chandra X-ray Observatories (CXO) launched by NASA in 1978, 1990 and 1999, respectively.

of thick material like Zerodur (glass with zero thermal expansion) to provide stiffness for maintaining the perfect shape. The four nested telescopes in *Chandra* are shown in *Figure* 3. *Chandra* has provided the finest X-ray images with a spatial resolution of 0.3 arcsec. An example is shown in the images of three clusters of bright, young stars that lie in the direction of the center of our Galaxy (*Figure* 4). Like many stars in the disk of the Galaxy, they are almost impossible to see with an optical telescope because of interstellar dust but are revealed in X-rays and infrared.

A much higher nesting (40 to 120 mirrors) within the same aperture or diameter (300 mm to 700 mm) of the largest paraboloid can be achieved by using substrates made of very thin foils. Use of thin foils leads to (a) savings in weight that is very

Figure 3. The 4 paraboloid mirrors of CXO (left) and diamond turning of one of the mirrors (right). These are the smoothest iridium-coated mirrors ever made. The focal length is 10m.



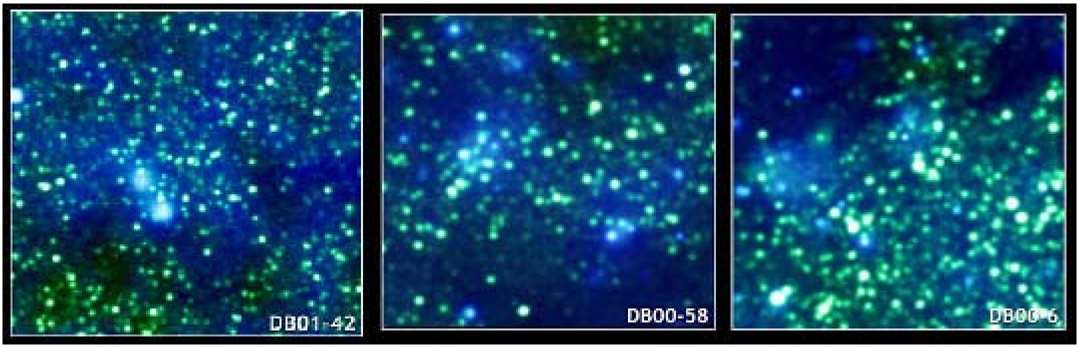
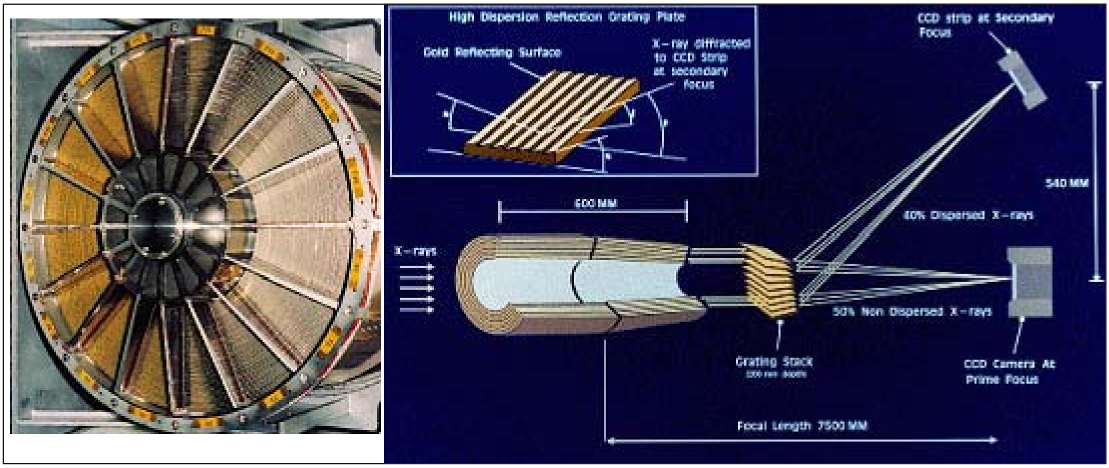


Figure 4. X-ray (blue) and infra-red (green) images of three star clusters 25000 light years away (size: 4.2 arcmin per side). X-rays are shown in blue and infrared in green. (For more X-ray images see the Suggested Reading).

important for a satellite mission, (b) savings in cost due to the ease of fabrication, as expensive diamond turning and figuring are not required, and (c) higher upper energy limit, since thin foils can be nested closer to the axis giving smaller grazing angles for reflecting higher energy photons. The mirror assembly for a telescope in the *XMM-Newton* used thin mirrors and is shown in *Figure* 5. The X-ray mirrors are gold-coated nickel shells and are produced via replication process as shown in *Figure* 6. A gold layer deposited on a highly polished master mandrel is transferred to the nickel shell that is electroformed on the gold layer. The master mandrels are made from double

Figure 5. The 58 mirrors of XMM-Newton (left) and light path for one of the 3 X-ray telescopes (right). The largest mirror in XMM-Newton *has a diameter of 70cm (left). Each mirror is 600mm long with thickness ranging from 0.47mm (innermost) to 1.07 mm (outermost). The total weight of the fully assembled mirror module (left) is 440 kg. The focal length is 7.5 meters (right). The spatial resolution is around 10 arcsec.*



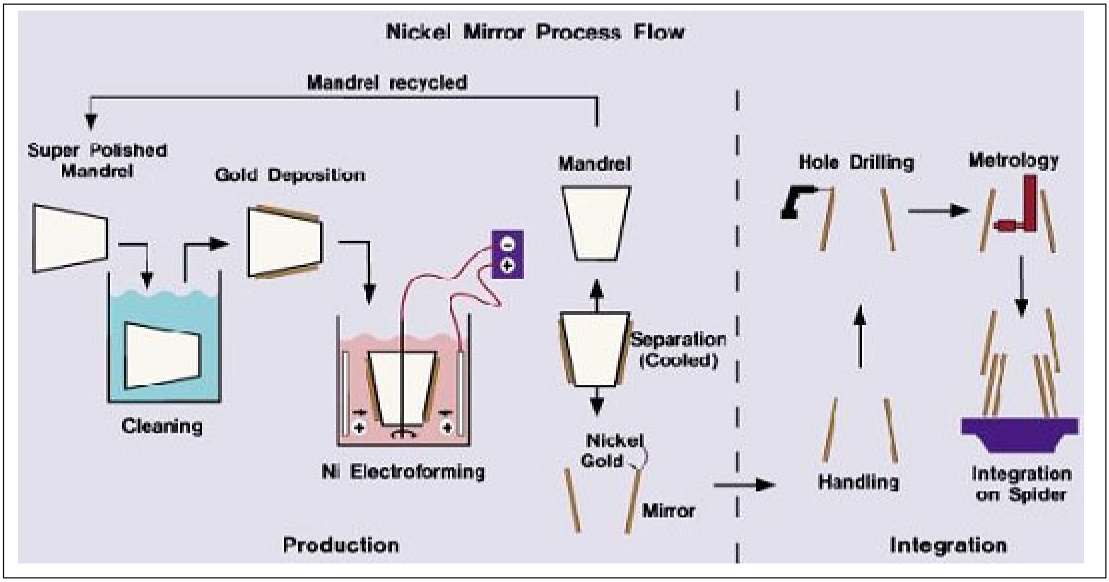
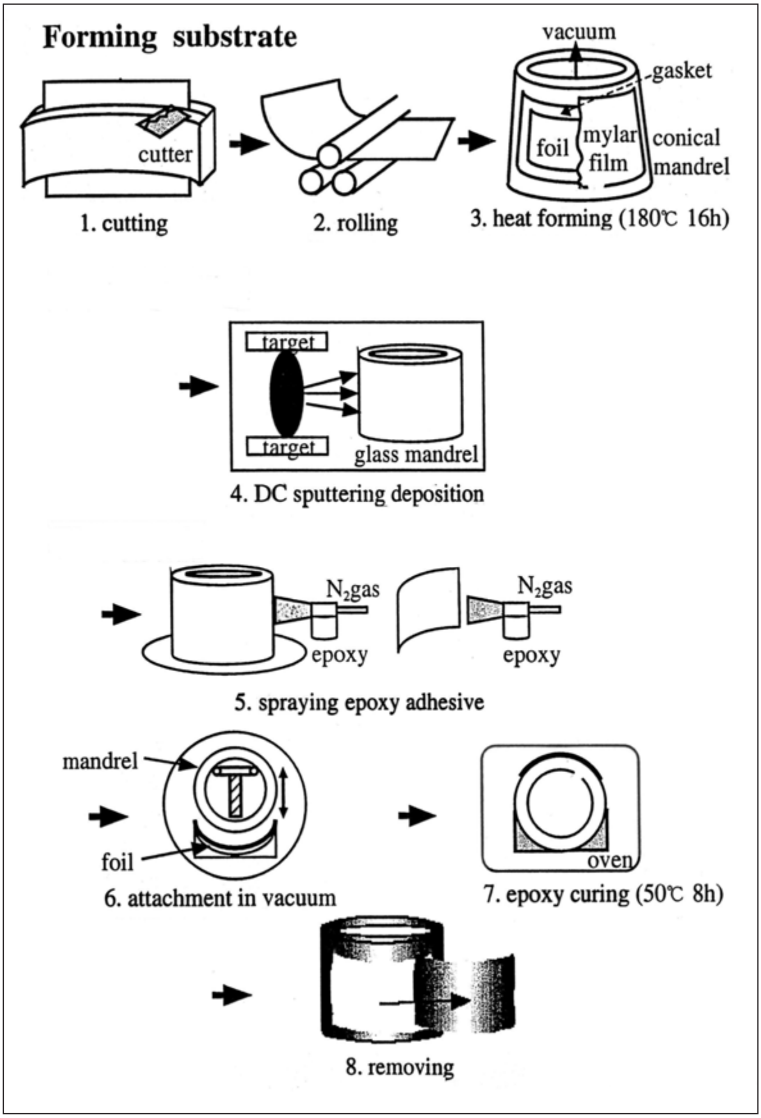


Figure 6. Production of mirrors for the XMM-Newton Observatory by a replication process.

conical Al blocks coated with Ni and lapped to exact paraboloid and hyperboloid shapes of Wolter I geometry, and then superpolished to a surface roughness of 4Å.

The telescopes in *ASCA (1993, Japan and USA)*, *ASTRO-E2 (Japan and USA)* and the *SXT* on *ASTROSAT (India)* have even thinner (0.15mm to 0.2mm) foils of gold-coated Al but figured in a conical approximation to Wolter I optics. The number of mirrors is 120 in *ASCA*, 168 in *ASTRO-E2*, and 41 in *SXT*. This results in even higher savings in weight (only 20 kg for a mirror module) but the spatial resolution obtainable with such telescopes is a few arcmin. In *ASCA* gold was deposited by evaporation and the surface was given a lacquer coating. Several improvements were made in *ASTRO-E2* by using replication process where a layer of gold deposited by sputtering on a smooth glass is transferred to Al via an epoxy coupling layer, thus replicating the smoothness of the glass surface on to the gold layer. The entire process is described in *Figure* 7, and is being used for making mirrors for *SXT* in my group at TIFR. A surface roughness of 10-15 Å has been achieved in this process. The spatial resolution of a telescope made with such mirrors is 3 arcmin *(ASCA)* and 1.5 arcmin *(ASTRO-E2)*.

Figure 7. Production of mirrors for ASTRO-E2 and SXT telescopes by epoxy replication.



The telescopes described in the previous paragraph are useful only for soft X-rays ($E<10$ keV). Presently hard X-ray astronomy uses either collimators or coded aperture masks to observe hard X-rays from astronomical sources. In these systems the internal detector background dominates the typical source fluxes because the collecting area and the detector areas are about the same. In a focusing system the collecting area can be 1000 times the detector area improving the sensitivity enormously. Focusing of hard X-rays (with energies $>$ 10 keV) using standard metal coatings is, however, difficult, since the grazing incidence angle decreases with energy, and for reasonable focal length the system becomes impractically long and the field of view very small. The effective area of the mirror also decreases and nesting becomes difficult. However, fabrication of a large number of such small diameter telescopes using electroformed Ni shells is being pursued in USA for the next generation hard X-ray telescopes. Super-mirrors or mirrors that can reflect hard X-rays can be made using multi-layered coatings. Bragg reflection from depth-graded multi-layers is used to increase the grazing angle over a broad energy range. Alternate layers of a high Z (like W, Mb, Ni) and a low Z (C, Si) materials with high and low refractive indices, and with bi-layer thickness varying over a wide range have to be used for multi-layered coatings on the soft X-ray mirror. Typically the thinnest layers (which reflect the highest energy X-rays) are deposited first, so as to minimize absorption due to the overlying coatings. The multi-layers are replicated on to Al foils from glass surfaces in the same way as described above for a single layer. This technology is currently being pursued for the next generation hard X-ray telescopes. True imaging of X-rays in the energy range of 10-100 keV will further widen our horizons and help us explore the universe where non-thermal emission from cosmic X-ray sources dominates.

Super-mirrors or mirrors that can reflect hard X-rays can be made using multi-layered coatings. Bragg reflection from depth-graded multi-layers is used to increase the grazing angle over a broad energy range.

Suggested Reading

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[7] http://chandra.harvard.edu/ for more on Chandra X-ray Observatory and the latest results from CXO.

[8] http://heasarc.gsfc.nasa.gov/ for details and links to all the X-ray observatories flown so far or being planned.

[9] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=23 for more on the XMM-Newton and the latest results from XMM.

The above references and sites are credited for the pictures and figures included here.

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