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HIGH-ENERGY ASTRONOMY FROM A LUNAR BASE

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Introduction

Astronomical investigations in the x-ray (0.2 to 100 keV) and gamma-ray (10^{-1} to 10^4 GeV) regions of the electromagnetic spectrum were made possible by spacecraft above the absorption of the Earth's atmosphere. For the future, x-ray and gamma-ray telescopes that are considerably larger and more massive than those currently under development for the next generation of satellite experiments are envisioned. Indeed, the collecting area of these instruments is limited by the size and weight capacity of current spacecraft rather than by any intrinsic difficulty in constructing larger detectors or telescopes. The virtually unlimited "real estate" of the lunar surface would accommodate instruments with considerably more capability than is possible on an Earth-orbiting platform. Consequently, a lunar base offers investigators the best opportunity to achieve the ultimate potential in high-energy astronomy.

First-generation high-energy astronomy observatories on the Moon will consist of telescope and detector components that are manufactured on Earth and aligned in situ. As a lunar manufacturing capability evolves, it may become possible to fabricate the heavy telescope components by using the Moon's low gravity and good vacuum.

The unlimited space of a lunar base as compared to an Earth-orbiting station offers the following advantages.

1. Large space: Many large-collecting-area x-ray and gamma-ray instruments can be accommodated at the same time.

2. Stable baseline: Long focal length between telescopes and detectors can result in configurations with very high resolving power.

3. Long duration: Inactive instruments need not be removed to make room for other telescopes needed.

4. Assembly of large instruments: Manned activity on the lunar surface is less difficult than extravehicular activities from a space station. Using common surveying techniques, lunar astronauts can align various components of a telescope system, change the configuration for other measurements, or incorporate improved technology.

5. Service: Sufficient space is available for a large supply of consumables, replacement parts, and dedicated computers.

6. Expandability: Telescope systems, particularly those of a modular type, can be developed incrementally in reserved spaces.

7. Observing: Continuous 14-day coverage of cosmic sources is possible.

The drawbacks of a lunar base – the cost of transporting cargo to the Moon and the difficulties of adapting to the day-night temperature extremes – would be ameliorated as transport capability improves and as more experience is gained on lunar surface operations. There is an intrinsic problem in that the absence of a magnetic field on the Moon results in a cosmic-ray background that is four times higher compared to near-Earth orbit. Although this increased background is disadvantageous to some x-ray and gamma-ray detector systems, it is not a major impediment for focusing x-ray telescopes or for gamma-ray telescopes which measure the arrival directions of individual photons. These telescopes are capable of discriminating against a diffuse background on the basis of the source's position.

X-Ray and Gamma-Ray Instruments

Three generic classes of instruments are optimum for deployment on a lunar base. They are systems with one or more of the following characteristics.

1. Very high throughput: Collecting area of 10^5 cm^2 or more

2. Very long focal length: Very high angular resolution when used in conjunction with occulting aperture masks

3. Broad sky coverage, 2π sr: Studies of temporal variability in many objects simultaneously, including burst sources, flares, and transients, as well as monitoring the activity cycles of many galactic and extragalactic sources

Photon fluxes (but not necessarily energy fluxes) of sources in the x-ray and gamma-ray bands tend to be relatively low compared to those of optical and radio-emitting objects. Hence, high throughput is a prerequisite for detailed astrophysical studies that go beyond merely detecting and cataloging sources. Investigators have stated that collecting areas exceeding 10^5 cm^2 are needed to satisfy their requirements in the next century. The objectives of such instruments include imaging, spectroscopy, and measurements of temporal variability.

An artist's conception of a high-throughput x-ray telescope system on the lunar surface is shown in figure 1. The instrument shown is the large-area modular array of reflectors (LAMAR), which consists of arrays of independent modules with imaging x-ray telescopes and detectors. Although the LAMAR is shown as a compact unit mounted in a single large pointing system, in practice, the array is more likely to be in a modular pointing system to facilitate service and insertion of gratings and crystals for spectroscopy and polarization measurements. A small version of the LAMAR with about 10^3 cm^2 of collecting area at an energy of 1 keV is being developed as a Space Shuttle experiment (ref. 1). This sketch (fig. 1) could represent other instruments as well, including coded-aperture devices for hard x-rays and low-energy gamma rays and a system of spark chambers for gamma rays with energies greater than 100 MeV. In contrast to the isolation afforded by a lunar base, it seems virtually impossible to accommodate and maintain all of these large systems in the close confinement of an Earth-orbit platform simultaneously for long periods without encountering mutual interference.

The angular resolution of a conventional x-ray telescope is limited by optical tolerances to perhaps 0.1 second of arc. Any further improvement would require a different approach, such as one based on occultation involving a long, stable baseline between apertures and detectors rather than on accuracy in the polishing process. For example, two 2-mm apertures separated by a 20-km baseline define a direction to within 0.02 arcsec. For wavelengths shorter than 0.4 nm, diffraction through 2-mm apertures will be below the level of 0.02 arcsec. It is possible to specify a variety of long-baseline instruments on the order of these dimensions that can achieve higher angular resolution over a limited angular range than is currently achievable by the best focusing telescopes.

One approach is shown in figure 2. The instrument is a variation of the scanning modulation collimator of the High-Energy Astronomy Observatory (HEAO-1 and HEAO-3) experiment (refs. 2 and 3) and is considerably larger. Rising or setting of sources caused by lunar rotation provides the scan. There is a 20-km baseline between two "picket fence" collimators that are presumed to be located near the equator of the Moon. The collimators are repetitively open for a distance of 2 mm and opaque for 6 mm. A 10^4-cm^2 moderate-resolution x-ray telescope, e.g., a subset of the LAMAR experiment (fig. 1), is behind the second collimator and serves as a detector.

The telescope, as compared to a nonimaging detector, eliminates background and confusion from multiple sources. If a point source is in the field of view, the modulated intensity of the image as a function of time is a series of perfect triangles as the Moon rotates. If the source has finite structure on a scale between 0.01 and 0.1 arcsec, it can be derived from a deconvolution of the shape of the modulation. Intrinsic time variations in the source are corrected by monitoring the source with a portion of the detector array that is outside the collimators. If the source can be tracked for 1° of lunar rotation, or 2 hours, as it rises or sets, there would be sufficient counts for studying the structure of the faintest extragalactic sources detected by the Einstein Observatory (HEAO-2). The objective of such studies is the structure of the central regions of quasars and other active galactic nuclei, including the existence of jets projecting from them. Resolving multiple images due to gravitational lensing effects is another objective.

The picket fence collimators have to be precisely periodic. For each degree of tracking, the distant one would either have to be 320 m high (at a 20-km distance) or have to move along a 320-m vertical track at a precisely known rate slightly different than that of the Moon's rotation. Alternatively, the nearer collimator and telescope could be placed on an elevator that is situated in a crater (fig. 3). The elevation of these instruments above the crater floor is adjusted to maintain the line of sight to the distant collimator along a constant direction on the celestial sphere as the source rises or sets. There are potentially hundreds of interesting sources in a 1° by 360° band of azimuth along the lunar equator. The amount of sky accessible to the instrument could be increased by providing a means of rotating the axis of the system off the lunar equator. In particular, the distant collimator is placed on a circumferential track around the near collimator-detector. Each 320-m segment of track length adds another 1° band of sky. A semicircle, or about 66 km of track, would bring nearly the full celestial sphere within reach of the instrument.

Although this particular instrument provides angular resolution in only one dimension, variations of this configuration can be effective for two dimensions. For example, the Japanese satellite *Hinotori* obtained x-ray images of the Sun with a rotating modulation collimator (ref. 4). In analogy to that instrument, the two widely separated collimators of the lunar-based observatory are slowly rotated about the same axial direction in space. Their rotation rates are synchronized to a common clock. The Fourier transform of the intensity modulations provides the high-resolution image. Obviously, many details need to be worked out, including the most practical means of rotating the collimators and determining whether they should be integral or modular. Simulation studies would clarify the resolving power of this configuration.

The first reaction of someone habituated to working within the limited confines of a laboratory or a satellite experiment is to be intimidated by "fences" and platforms that can be elevated 320 m or tracks that are many kilometers long. However, these items are not at all unusual to the transportation and building construction industries. If a lunar base is developed, the necessary tools are likely to already be present. Furthermore, the problem of constructing tall fences and high elevators is eased by the low lunar gravity.

The preceding example is merely illustrative of many possibilities for achieving higher angular resolution with long-baseline observatories on the lunar surface. A narrow field of view, multiple-pinhole camera or Fresnel zone plates are other possibilities. A large high-energy gamma-ray telescope, for example, an expanded version of the EGRET instrument of the Gamma-Ray Observatory (ref. 5) and a telescope under study for the Space Shuttle external tank (ref. 6) can function extremely well in the vacuum and the weak magnetic field of the Moon. A gamma ray is converted into an electron-positron pair, which then travels in straight lines for long distances. The coordinates along their paths can be detected in spark or proportional chambers to define the incident gamma-ray direction with excellent precision. This is perhaps the only possibility for obtaining the precise positions needed for optical identification of high-energy gamma-ray sources near the galactic equator.

The third general class of instrument is an "all-sky detector." Within the next decade, a great deal of additional information on the temporal behavior of many x-ray objects is expected from Japan's ASTRO-C and the U.S. X-ray Timing Explorer (XTE) satellites. The ultimate instrument is one that combines the resolution of the small-area wide-field cameras of these satellites with the throughput of their large-area detectors, which have small fields of view. The instrument should be capable of resolving thousands of objects simultaneously and providing 10^4 cm^2 of effective area for studying the temporal behavior of many objects without problems of excessive background or source confusion. An example of such an instrument for x-rays is shown in figure 4. It is based on concepts proposed by W. Schmidt (ref. 7) of the Max-Planck Institute and on the "lobster eye" camera of R. Angel (ref. 8) of the Stewart Observatory. This particular device is a hybrid in that it images in one dimension by focusing, whereas a circumferential, pseudorandom collimator with open bands along the axis of the cylinder acts as a coded aperture for angular resolution in the other dimension (ref. 9).

Because individual photons are being detected from thousands of sources simultaneously with their position, energy, and arrival time information encoded to high precision, the quantity of data flowing from the instrument is enormous. A dedicated supercomputer would be needed for processing this data stream in real time and for extracting the essential results. Information on transient events is needed with minimum delay so that it can be transmitted to other observers. Indeed, the coordinates of a given object are needed at the lunar base so that other detectors, including optical and ultraviolet telescopes, can be pointed at a source which is exhibiting gamma-ray or x-ray activity.

Conclusions

A lunar base is the optimum locale for the deployment of the ultimate high-throughput x-ray and gamma-ray instruments. The virtually unlimited space would permit the construction of telescope systems with a collecting area that is, at least, two orders of magnitude more than that of observatories currently in the planning stages for Earth orbit. A stable, very long baseline will also enable achievement of better angular resolution than is currently possible.

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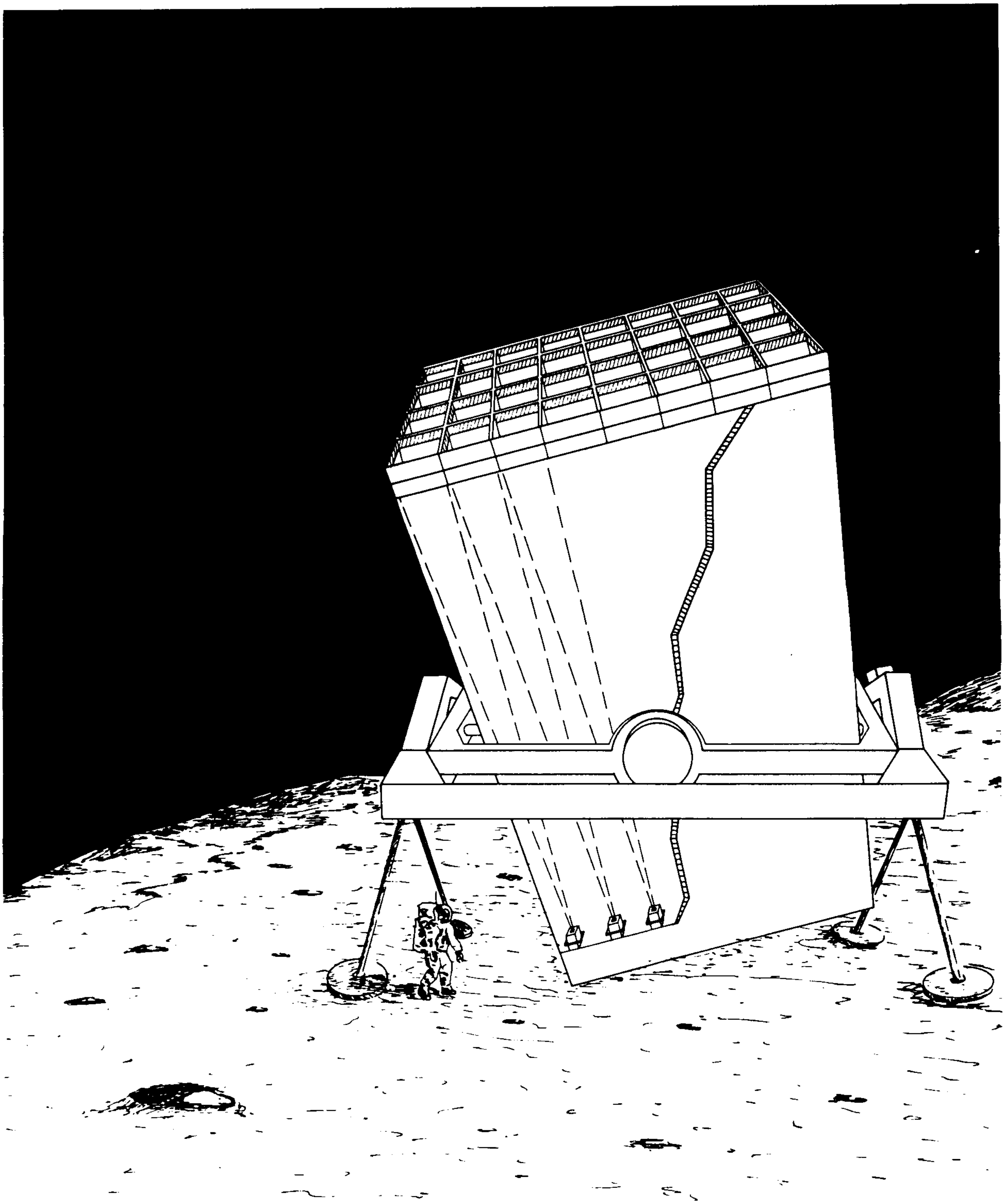

Figure 1.- Artist's conception of a lunar-based LAMAR. As the Moon rotates, sources are maintained within the telescope fields of view by a pointing system. The collecting area of a lunar-based facility can be much greater than those of the next generation of Earth-orbiting x-ray and gamma-ray telescopes.

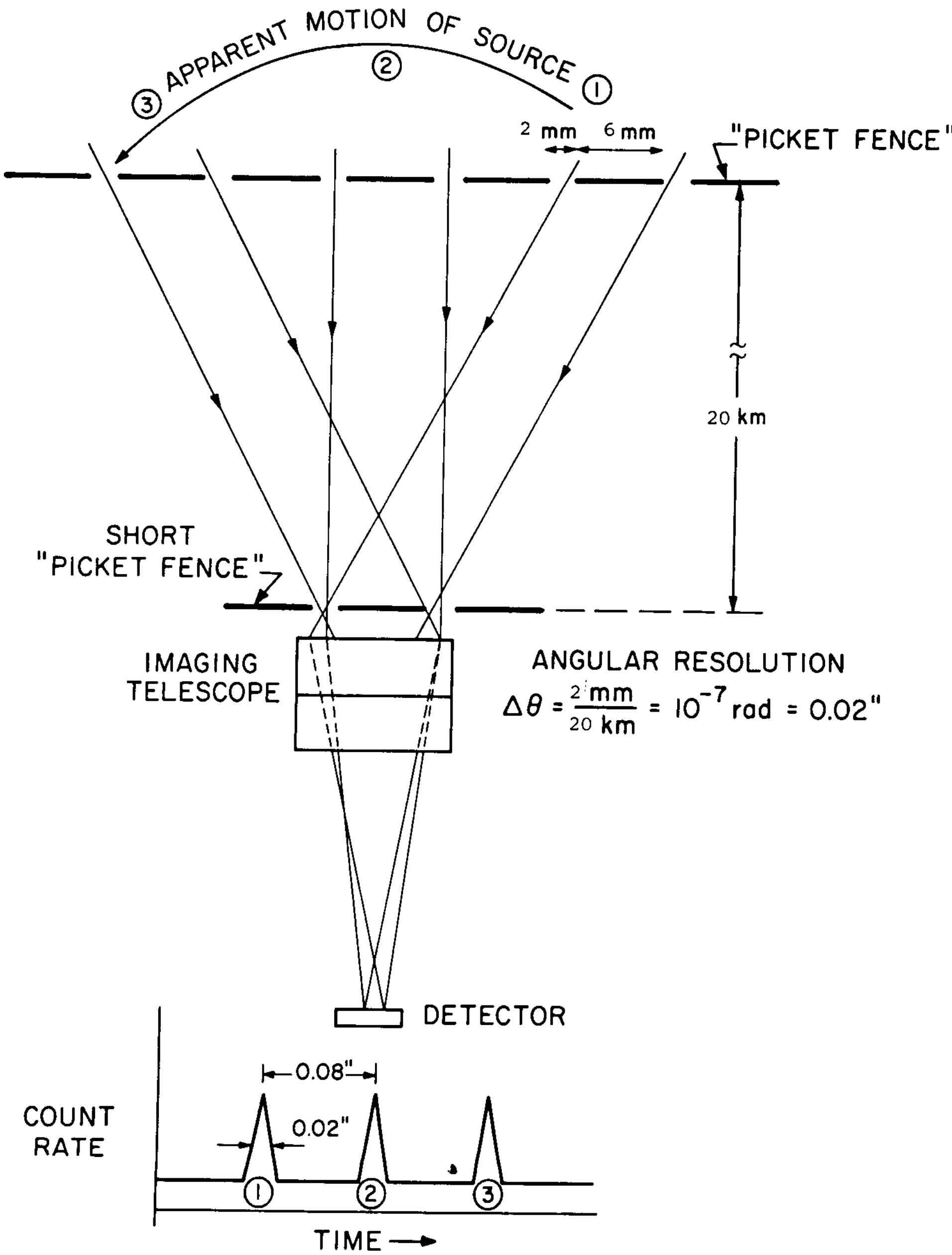

Figure 2.- Plan view of long-baseline system with very high angular resolution. Because flux transmitted through two "picket fence" collimators is modulated by lunar rotation, x-rays having wavelengths of 0.4 nm or less are not diffracted significantly. Deconvolution of the modulations reveals the structure of the source in one dimension to a resolution of 0.02 arcsec or less. This resolution is far better than can be achieved by conventional x-ray telescopes Synchronized rotation of the two collimators about a common axis could, in principle, provide imaging information in two dimensions.

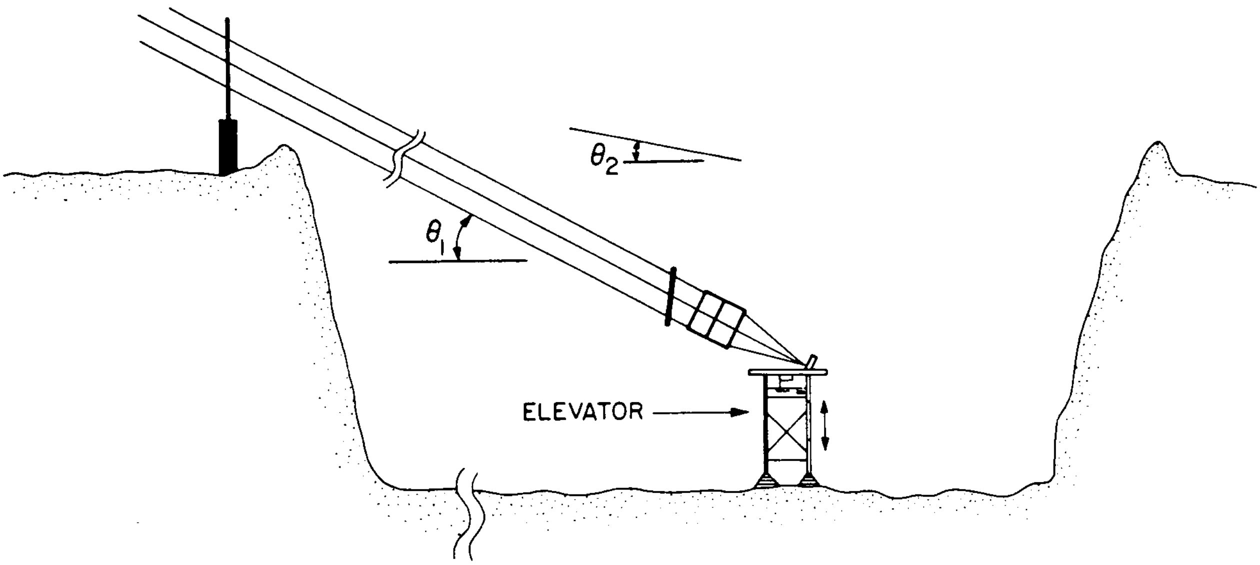

Figure 3.- Profile view of long-baseline system shown in figure 2. The elevation of the second collimator (short "picket fence") and the detector is varied with respect to the floor of a crater so as to remain pointed at a source as it rises or sets between angles θ_1 and θ_2.

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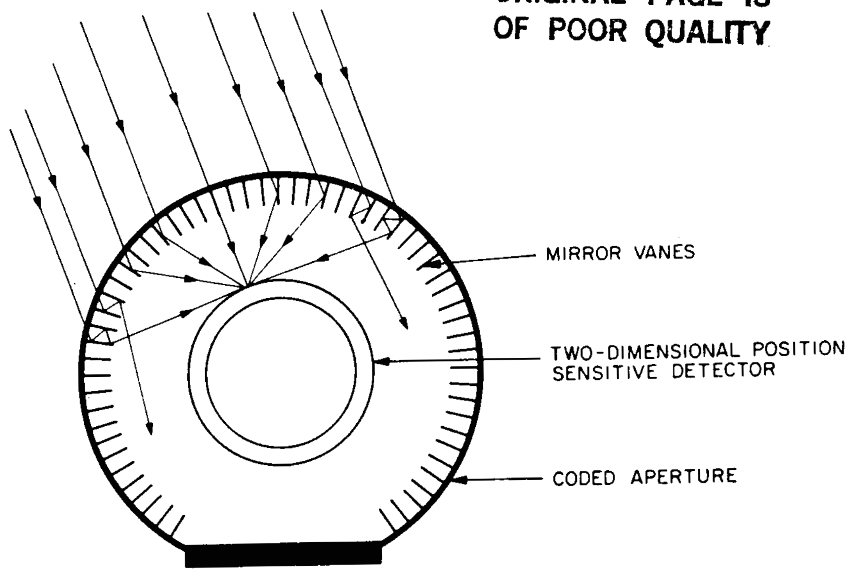

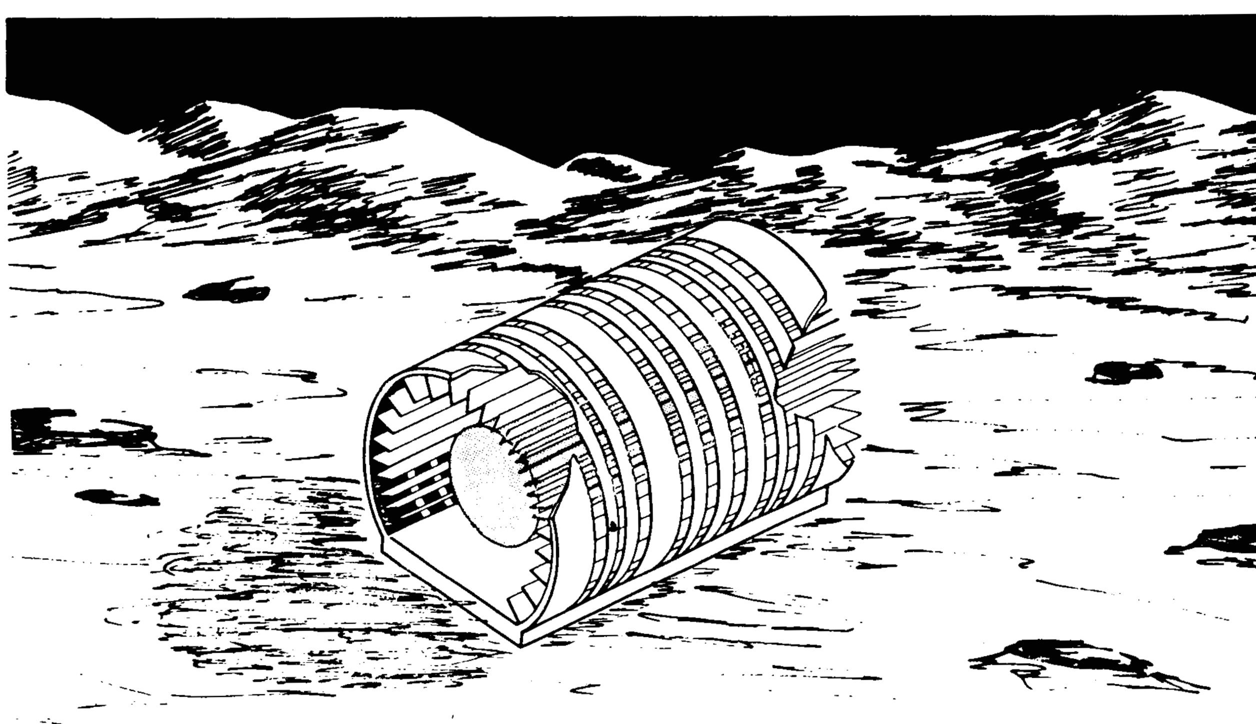

Figure 4.- A large-area, wide-field x-ray camera system fixed on the lunar surface. The camera focuses in one dimension, as described in reference 7, and has a coded aperture for angular resolution in the other dimension. This instrument is capable of monitoring temporal variations of many sources simultaneously. The maximum angle of reflection, actually about 1°, appears greatly exaggerated in the figure.