Grazing Incidence X-Ray Telescopes

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This paper reviews some of the work related to X-ray imaging which has been done at our laboratory over the past several years. Our interest has been to develop high resolution telescopes for studying X-ray emission from the sun and from other celestial X-ray sources. The systems which we have developed are based on the fact that X-rays are reflected with high efficiencies only at grazing angles of incidence.

Fig. 1 shows the calculated reflection efficiency for various materials (Be, Al, Ni, Au) at various grazing angles as a function of wavelength [1]. The telescopes which we are using now have a Kanigen [2] coated beryllium reflecting surface. The reflecting surface is tilted approximately 1 degree with respect to the optical axis; therefore, these systems have a short-wave cutoff on the order of 3 Å. The long-wave cutoff is determined by a filter placed in the optical path.

The requirement for shallow angles of incidence precludes the use of normal mirror geometries. Our mirror system is a double reflection system shown schematically in Fig. 2. The two reflecting surfaces are a paraboloid and, confocal to it, a hyperboloid. This design was first suggested by H. Wolter [3]. A single paraboloid used at grazing incidence is subject to severe coma; the second reflecting surface, the hyperboloid, corrects for this aberration. The mirror design requires that the optical axes of the paraboloid and hyperboloid coincide and that the focus of the paraboloid coincide with the focus of the other sheet of the hyperboloid. A mirror system of this type will provide high angular resolution over a narrow field of view. To maximize the reflection efficiency for a given mirror diameter and focal length, our mirrors are designed to have paraxial rays strike both reflecting surfaces at the same angle of incidence; therefore, the average
hyperboloid slope is three times that of the paraboloid. Diameters of mirror systems we have built range from 7.5 cm to 23 cm. The geometrical image quality is not affected by a uniform scaling of the mirror but by changes in the average slope (i.e. ratio of diameter to focal length) and by changes in the ratio of diameter to length of the mirror element. For practical reasons, to minimize polishing, the mirror slope will be as large as possible consistent with the acceptable short wavelength cutoff.

Calculated blur circle plots for a mirror with a focal length to diameter ratio of 10:1 and a reflecting element length to diameter ratio of 1:1 are shown in Fig. 3. A bundle of 60 parallel rays evenly spaced over the telescope aperture was used in the ray tracing program. On-axis rays image to a point; off-axis rays image in a sharply peaked intensity distribution. The blur circle diameter is approximately 6 arc seconds for rays incident five minutes off axis and 18 arc seconds for rays incident ten minutes off axis. Since the image intensity distribution is sharply peaked, the image resolution will be significantly better than the blur circle diameter. The distance of the striking points of individual rays from the center of the image is approximately proportional to the distance from the point of first reflection to the plane of intersection of the parabola and hyperbola. Therefore, the blur circle is directly proportional to the length of the reflecting elements. The blur circle diameter for a beam of parallel rays (point source at infinity) as a function of the angular displacement of the beam from the optical axis is shown in Curve A of Fig. 4. An improvement in off-axis imaging can be made at the expense of on-axis imaging by slightly displacing the focal plane, as shown in Curve B. A more substantial improvement can be made by suitably curving the focal surface, as shown in Curve C.

While one can readily design an X-ray telescope with a high reflection efficiency and a resolution of a few arc seconds over a field of view of many arc minutes, the problem of actually fabricating the required optical surfaces is formidable. The initial mirrors which were fabricated in the period from 1960 to 1962 had a resolution of a few arc minutes, and it is only within the last year we obtained mirrors with a resolution of a few arc seconds. To obtain diffraction limited image quality, one should have a surface sufficiently close to the theoretical surface so that the phase difference introduced in the reflected wave by surface irregularities is a small fraction of a wavelength. If we consider a quarter wave error tolerable, then the allowable height of a surface deviation is 85 Å for a mirror with an average slope of 1" and an X-ray wavelength of 12 angstroms. This is approximately 1/60 wave in visible light.