— a value that is close to the theoretical limit.

In astronomy, it is angular resolution that is important. For X-rays, the best available angular resolution (0.5 arc seconds (arcsec) with the Chandra observatory[5]) is about 10^4 times worse than the diffraction limit. There are good reasons for trying to do better: attaining one of astronomy's 'holy grails' — to 'see' a black hole by imaging the space-time around the supermassive objects at the centres of active galaxies — would require resolution below 1 micro-arcsec, corresponding to the diffraction limit for a 60-cm-diameter system using 500-keV γ-rays, or a 60-m-diameter one using 5-keV X-rays.

In microscopy, the best resolution is obtained using Fresnel zone plates and the closely related phase Fresnel lenses. These are highly chromatic, with a focal length that is inversely proportional to wavelength, so the best resolution is obtained with essentially monochromatic radiation. Wang et al.[1] have proposed a scheme for making an achromatic X-ray lens by combining a Fresnel lens with a refractive component (Fig. 1). Such lenses should have the same high resolution but with a larger useful bandwidth.

Fresnel lenses have also been considered for high-energy astronomy[2,3,6], and the achromatic Fresnel lens scheme suggested by Wang et al. has also been proposed in that context[3]. Figure 1 shows a general achromatic lens scheme of this type. It has even been shown (L. Speybroeck, unpublished work, and ref. 6) that the second derivative of focal length, as well as the first, can be corrected by separating the two components — a configuration that may also find application in microscopy.

The achromatic configuration proposed for microscopy differs in one detail. Wang et al. suggest taking advantage of the high dispersion that occurs close to X-ray absorption edges. Over wider bands and for short wavelengths, λ, the dispersion, D, that they define is close to zero, but correction remains possible because of the λ^{-2} component in
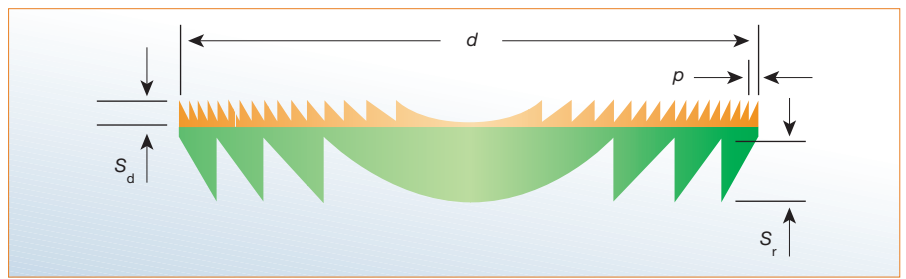

Figure 1 An achromatic refractive/diffractive lens. The diffractive component (orange) could be a phase Fresnel lens (as shown) or a (phase) zone plate. The refractive component (green) is stepped to avoid excessive absorption. Its curvature is exaggerated here for clarity. The same principle can be used both in astronomy[3] and in microscopy/microlithography[1], but with different parameters (Table 1). In the microscope objective case, stepping the refractive component introduces no error; in the astronomical case, some resolution is lost, but multiple passbands increase the throughput. d, Diameter of the lens; S_d and S_r are the depth of the steps in the diffractive and refractive components, respectively, and correspond to phase shifts of an integer number of cycles at the nominal wavelength; p is the finest pitch of the diffractive element.

the expression for the focal length, f. The radii of curvature of the refractive components are much less favourable, but in astronomy the considerations are different. Spatial resolution, which is of interest in microscopy, depends on $\lambda f/d$, where d is the diameter of the lens, whereas angular resolution depends only on λ/d. Thus, long focal lengths can be used for astronomy, minimizing both the chromatic aberration that requires correction and the curvature of the components needed to correct it. Furthermore, with large d and short λ, micro-arcsec resolution does not necessarily require perfect phase coherence.

Building a micro-arcsec telescope based on a Fresnel lens will not be easy. The focal length could be up to a million kilometres, and two or three separate satellites carrying the lens(es) and the focal plane array will have to be positioned with centimetre accuracy. But micro-arcsec imaging is an important target (NASA recently included a black-hole imager in its SEUS Roadmap[7]) and other approaches to achieving this goal, such as an X-ray interferometer carried on a flotilla of spacecraft[8,9], have requirements that are just as extreme, if not more so.

Although overall system performance, including spacecraft positioning for example, will have to be taken into account, for Fresnel-lens-based telescopes the purely optical performance can be predicted with confidence. The basic physical principle has already been demonstrated in microscopy, where achromatic lenses will presumably also soon come into use. The different requirements of astronomy merely require a change of scale: lenses of many metres in diameter with millimetre-scale zones, instead of sub-millimetre lenses with zones of the order of 50 nm (Table 1). Constructional tolerances will be correspondingly easier to achieve.

An achromatic Fresnel-lens telescope measuring 10^{11} m in length will certainly not be built very soon. Perhaps experience with lenses that are limited by diffraction at the nanometre scale will give us the confidence to proceed to imaging black holes with millions of times the mass of our Sun.

Gerry Skinner*, **Paul Gorenstein**†
*Centre d'Étude Spatiale des Rayonnements, Toulouse 31208, France
e-mail: skinner@cesr.fr
†Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA

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Table 1 Lens parameters for astronomy and microscopy/microlithography

	Astronomy[3]	Microscopy[1]
Lens diameter	5 m	1 mm
Focal length at nominal wavelength	+40,000 km	+22.475 mm
Wavelength, λ (photon energy)	0.062 nm (20 keV)	1.335 nm (929 eV)
Theoretical resolution	5×10^{-6} arcsec	35 nm
Diffractive component		
Pitch at edge	0.5 mm	60 nm
Focal length	+20,000 km	+22.475 mm
Refractive component		
Material	Polycarbonate	Copper
Focal length	−40,000 km	—
Maximum thickness*	20 mm	<1 μm

Apart from the obviously disparate scales, the differences are driven by the dispersion $Z=(d\delta/d\lambda)(\lambda/\delta)$, where $\delta=1-\mu$ and μ is the refractive index. We adopt this measure of dispersion instead of the parameter $D=df_1/d\lambda$ used in ref. 1 as it includes the dispersion present even at short wavelengths, where the atomic scattering factor f_1 is constant. Well above absorption edges (astronomy), Z is very close to −2, independent of the material. In the band close to the copper L absorption edge (microscopy/microlithography), Z is large and varies in the range −800 to +250.
*Based on 50% mean transmission.