*Galaxies and Their Constituents at the Highest Angular Resolutions*
*IAU Symposium, Vol. 205, 2001*
*R.T. Schilizzi, S. Vogel, F. Paresce and M. Elvis*

# Prospects for High Angular Resolution in Gamma-ray Astronomy

G. K. Skinner

*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, England*

**Abstract.**
It is in the gamma-ray band, the shortest wavelength part of the electromagnetic spectrum, where diffraction limitations are least constraining, that one might hope for the highest angular resolution. The intrinsic limitations of the imaging techniques used in gamma-ray astronomy are reviewed and the feasibility of obtaining diffraction-limited angular resolution in this band discussed. It is argued that by accepting the necessity of extremely long focal lengths, sub micro arc second resolution along with enormously improved sensitivity should be achievable using diffractive lenses.

## 1. Introduction

From the point of view of diffraction, the gamma-ray band should be the one in which it is easiest to obtain high angular resolution. However, the resolution of present generation gamma-ray instrumentation and of that foreseen in the near future far is inferior to that in other wavebands. Astronomy is clearly difficult when conducted with telescopes that can barely distinguish between objects with the angular scale of the moon and those with the angular scale of stars! Progress has been possible only because, with present sensitivity, the gamma-ray sky is rather sparsely populated and through using signatures in the time and energy domains.

The angular resolution currently achieved in the gamma-ray band is 9–10 orders of magnitude worse than the diffraction limit for $\sim$ metre sized instruments. If that limit could be approached, gamma-ray instruments could offer the micro arc second ($\mu''$) resolution necessary to investigate, for example, the structure around the event horizons in black holes.

This review will consider the factors which in practice limit the angular resolution attainable with different techniques for gamma- ray imaging and prospects for overcoming these limitations. Emphasis will be on the prospects for major improvements, allowing the state of the art to progress into the $\mu''$ domain, rather than considering how factors of a few might be gained. For the present purposes the gamma-ray band will be considered to stretch from 0.1–10 MeV and higher energies will not be considered in any detail.

## 2. Limiting Factors

It will be seen below that two factors enter frequently into expressions for the angular resolution attainable with a particular technique:

*Detector Spatial Resolution* Recording the interaction point of a photon in a detector in practice involves detecting an electron which has been given energy in a photo-electric absorption, in a Compton scattering or in pair creation. The electron track length is approximately proportional to $E^{0.8}$ and inversely proportional to density. For a $E$ =1 MeV electron in silicon it is about 1.8 mm. Scattering reduces the extent to which one can do better than simply finding the centroid of the enrgy deposit. Here 1 mm will be used as an example of the spatial resolution achievable in principle.

*Telescope Length* The length of the telescope is frequently decisive in dictating the angular resolution attainable. The feasibility of placing an optic and the detector on separate spacecraft has been demonstrated in studies of the XEUS mission, in which a station-keeping spacecraft will maintain a detector at the focal point of a mirror 50 m away on another spacecraft. XEUS will be in low earth orbit; much larger separations are practicable away from the earth and LISA will use a 3 spacecraft on a triangle with sides of $5 \times 10^6$ km. It will be supposed here that separations of $10^3$–$10^6$ km or more are possible if necessary.

## 3. Gamma-ray Imaging Techniques

The imaging techniques which have been used or proposed for gamma-ray imaging are listed in Table 1, along with an indication of the angular resolution of current or near future instruments using the technique. The limiting factors for each are reviewed below. The factors will be quantified in terms of the photon energy $E_{MeV}$ measured in MeV, the detector spatial resolution $r_{mm}$ in mm, a characteristic length $l_9$ in units of $10^6$ km ($10^9$ m) and other parameters defined as necessary.

Table 1. Imaging techniques for gamma-ray astronomy, the angular resolution of current (or near future) instruments and indicative potential performance

| Technique | Example instrument(s) | Note | Angular resolution ($''$) Current | Potential |
|---|---|---|---|---|
| Compton Telescope | Comptel | | 4000 | 1000 |
| Particle tracking | EGRET, GLAST | | 1000 | 1000 |
| Multilayer optics | InFocus, HEFT | Balloon | 60 | 1 |
| Laue diffraction | Claire | Balloon | 20 | 1 |
| Coded Mask | Integral IBIS | | 700 | $< 10^{-3}$ |
| RMC | HESSI | Solar | 2 (40 keV)<br>36 (10 MeV) | $< 10^{-3}$ |
| Diffractive optics | (X-ray only to date) | Lab.<br>Solar [1] | 10<br>20 | $< 10^{-6}$ |

[1] Only known use for high energy astronomy (Krämer et al. 1978)

https://doi.org/10.1017/S0074180900221773 Published online by Cambridge University Press

### 3.1. Compton Telescopes and Particle Tracking Detectors

In a Compton telescope uncertainties arise because of the finite spatial resolution of the two detectors needed to deduce the scattered photon direction and because of the scattering angle uncertainty resulting from detector energy resolution and from the unknown initial momentum of the scattering electron. There seems to be no prospect of improving the resolution beyond $\sim$10 arc minutes.

Instruments which track the positron and electron following a photon absorption by pair-production (e.g. EGRET, GLAST) are only efficient above the energy range under consideration here but anyway because of scattering uncertainties they are unlikely to be any better in angular resolution than Compton telescopes.

### 3.2. Grazing incidence optics

In the X-ray band total external reflection at grazing incidence is used to construct high resolution optical systems (e.g. AXAF). In the gamma-ray band the real part of the refractive index of any material of density $\rho$ g cm$^{-3}$ is $(1-\delta)$ where $\delta \sim 2\times10^{-10}\rho(2Z/A)E_{Mev}^{-2}$ leading to grazing angles of only $20E_{MeV}^{-1}$ arc seconds even for the most favourable materials (e.g. Iridium).

Higher grazing angles can be used with surfaces coated with 'multilayers' in which reflections from successive interfaces between high and low refractive index material, though individually weak, add coherently. Even so, the area of surface to be coated exceeds the effective area by a very large factor.

The resolution attainable is limited by the precision of the substrate and of the layer deposition. At present balloon flight tests of systems working to $\sim$100 keV and with angular resolution at the 1 arc minute level are under preparation. It is difficult to imagine resolution significantly better than 1 arc second being achieved.

### 3.3. Laue and Bragg diffraction

A lens based on Laue diffraction in many small, carefully oriented, crystals and capable of focussing 170 keV gamma-rays onto a small, low background, detector has been successfully flown on a balloon (Laporte et al. 1998; vonBallmoos et al. 2000). Although the imaging capabilities of this technique are limited, it can certainly be extended to concentrating gamma-rays of higher energies. A 2 m diameter lens working at 1 MeV might have a focal length of 'only' 80 m.

The angular resolution obtainable with this technique depends on the degree of perfection in the crystals, which can be measured by the 'rocking-curve width'. Highly perfect crystals of $\sim$0.1 m size can be obtained in the form of dislocation-free silicon and if mounted without stress and without thermal distortion they should have extremely narrow rocking curves. Unfortunately the energy bandwidth also depends on the rocking curve and would be disappearingly small. In addition the crystals would have to be aligned with a precision comparable to the desired resolution.

This technique (and perhaps its counterpart using Bragg geometry) is likely to prove crucial in making flux concentrators for specific gamma-ray energies but is unlikely to fullfil the need for very high angular resolution imaging.

### 3.4. Coded Mask Telescopes

For a coded mask telescope, the most obvious limitation to the angular resolution is the characteristic angle subtended by a mask hole, size $a_{mm}$ at the distance of the detector:

$$\theta_m = 0.21\ a_{mm}\ l_9^{-1} \quad \mu''. \tag{1}$$

Because the detector spatial resolution will not be perfect, there is another term

$$\theta_r = 0.21\ r_{mm}\ l_9^{-1} \quad \mu''. \tag{2}$$

When one considers diffraction, it is the aperture size of a single hole which matters. Using the usual formula for the Rayleigh limit in the case of a circular pinhole to give a representative measure of this effect, we find

$$\theta_d = 312\ a_{mm}^{-1}\ E_{MeV}^{-1} \quad \mu'' \tag{3}$$

These terms need to be combined to form the net resolution. To a first approximation one may take $\theta^2 = \theta_m^2 + \theta_r^2 + \theta_d^2$.

To avoid the loss in sensitivity which arises if the holes are too small compared with the detector resolution (Skinner 1995), one would normally arrange that $a > r$, so $\theta_r < \theta_m$. If the mask holes are very small the diffraction term will dominate, if they are too large the mask hole size one will. For the best possible resolution, one may aim for $\theta_m \sim \theta_d$. With these conditions one obtains:

$$l_9 > 6.6 \times 10^{-4}\ r_{mm}^2\ E_{MeV} \tag{4}$$

$$\theta_d = 8\ l_9^{-1/2}\ E_{MeV}^{-1/2} \quad \mu''. \tag{5}$$

Thus with large separations between mask and detector, milli-arc- second or better performance can be envisaged from coded mask systems. The limitation though is one of sensitivity. Because there is no concentration of flux every pixel of the detector contributes noise to every image pixel.

### 3.5. Rotation Modulation Collimators (RMCs) and related devices

Devices such as RMCs avoid any dependence on having a detector with high spatial resolution by not attempting to record the shadow of a modulator directly. In the case of the RMC, for example, a grid is placed at the front of the telescope and a second grid is used in front of the detector which is matched or nearly matched to the pitch of the shadow first.

A variation on the RMC is to replace the two grids by masks with a pattern similar to that used in Zone Plates (Desai et al. 1998). In this way a Moiré fringe pattern is obtained which is a close approximation to a Fourier Transform of the object field.

If ultra-high resolution is sought by making the system very long and using a fine pattern then the wave nature of the radiation must be taken into account. The first grid of an RMC, for example, acts like a diffraction grating and it is the near field shadow of this which falls on the second grid.

Within small numerical factors the equations and the limitations are essentially the same as for coded mask telescopes, without the detector resolution term and with the modulator pitch replacing the mask hole size.

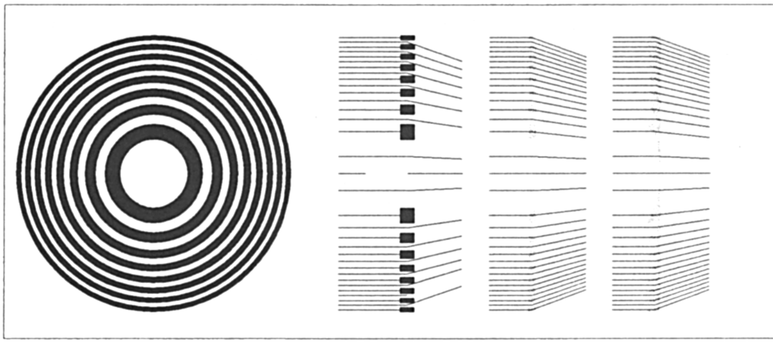

Figure 1. Diffractive Optics: Zone plate (maximum efficiency 10%), Phase Zone Plate (40%) and Phase Fresnel Lens (100%)

### 3.6. Diffractive optics

The technique which seems to have the most promise for high angular resolution at gamma-ray energies is the use of diffractive lenses (Figure 1). In these the radiation which would arrive at the focal spot with the wrong phase is blocked (Zone-plates) or is given a phase shift by passing through an appropriate thickness of material with a refractive index which differs from unity (Phase Zone Plates, or Phase Fresnel Lenses, PFLs).

Lenses based on these principles are increasing used at synchrotron facilities, particularly for X-ray microscopy. The implications of the application of this technique to gamma-ray astronomy are considered in more detail elsewhere (Skinner 2000). Briefly, one finds that PFLs can have high efficiency at gamma-ray energies because although the thickness of material for the maximum required phase shift of $2\pi$ increases with energy, the absorption losses become small (Figure 2). For a lens of diameter $d_m$ m, the diffraction limit is

$$\theta_d = 0.31 d_m^{-1} E_{MeV}^{-1} \quad \mu'' \tag{6}$$

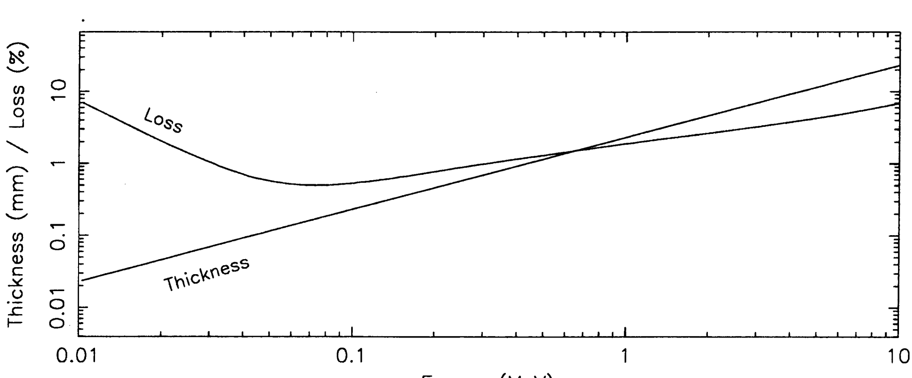


Figure 2. The thickness of aluminium necessary to introduce a $2\pi$ phase shift as a function of gamma-ray energy, and the absorption losses in an aluminium PFL designed for that energy.

and there seems to be no reason why performance close to this limit should not be achieved with lenses several metres in diameter. The two most serious problems are

(i) The focal lengths are extremely long. For a lens with finest zone pitch $p_{mm}$ (in mm)

$$l_9 = 0.40\ p_{mm}\ d_m\ E_{MeV} \quad \mu'' \tag{7}$$

(ii) The lens is highly chromatic, having a focal length proportional to energy. Consequently for a particular focal plane position the focussing is imperfect outside a narrow energy band, leading to an angular resolution contribution

$$\theta_{\Delta E} \sim 0.5\ d_m\ l_9^{-1}\ (\Delta E/E)_{\%} \quad \mu'' \tag{8}$$

The restricted bandpass reduces the sensitivity for continuum sources, though this can still be very good. If the long focal length is accepted the preformance of a system based on these principles can be impressive, as seen from Table ??.

Table 2. Parameters of an example system based on an PFL diffractive lens working at 500 keV. Assumed detector resolution $r = 1\ mm$. Parameters in italics are affected by chromatic aberration and two values are given, for monochromatic radiation and for $\Delta E/E = 1\%$.

| Lens | | | | Angular resolution | |
|---|---|---|---|---|---|
| Diameter | 5 m | Material | Aluminium | Diffraction limit | 0.06 $\mu''$ |
| Thickness | 1.2 mm | Minimum pitch | 2.5 mm | *Chromatic aber.* | 0/0.8 $\mu''$ |
| Efficiency | ~99% | Focal length | $5 \times 10^6$ km | Detector limit | 0.04 $\mu''$ |
| *Focal Spot* | 1.5/20 mm | *Concentration* | $10^7/6 \times 10^4$ | Net | 0.07/0.8 $\mu''$ |

## 4. Conclusions

If long telescope systems are accepted, coded mask systems should be capable of milli arc second performance, but will have limited sensitivity. With the capability of concentrating flux onto a small region of the detector plane, diffractive lenses can overcome this problem and at the same time offer micro arc second performance or better. If the challenges of spacecraft control and telescope pointing determination can be overcome, an optically simple system using this technique could finally allow the potential of the gamma-ray band for ultra-high resolution observations to be realised.

## References


Desai, U., Orwig, L.E., Piquet, L., & Gaither, C.C. 1998, Proc SPIE, 3442, 94

Krämer, G., Einighammer, H.J., Elwert, G, Bräuninger, H., & Trümper, J. 1978, Solar Phys. 57, 345

Skinner, G.K., 1995, Experimental Astron. 6, 1

Skinner, G.K., 2000, A&A, submitted

Laporte, P. et al. 1998, Astro. Lett. and Commun., 39, 453

von Ballmoos, P., et al. 2000, in Proc 4th Integral Workshop, to be published.


https://doi.org/10.1017/S0074180900221773 Published online by Cambridge University Press