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Prospects for γ-ray imaging telescopes

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Localized sources of γ-radiation have been detected by both satellite and balloon-borne detectors but very few of these sources have been identified with known astronomical objects. Two of the objects listed in the second COS-B catalogue of γ-ray sources (Swanenburg *et al.* 1981) have been linked with the Crab and Vela pulsars because of their characteristic variability, and one other has been fairly confidently associated with 3C273 (Swanenberg *et al.* 1978; Bignami *et al.* 1981). Another object is probably located in the ρ-Oph cloud complex (Mayer-Hasselwander *et al.* 1980; Bignami & Morfill 1980). Although the angular resolution of the COS-B telescope is typically ± 5° for 100 MeV photons, more precise estimates of the most likely location of γ-ray sources have been made by applying image processing techniques. Nevertheless, the best error boxes include of the order of 1000 stars having a magnitude $m < 15$ and a much higher angular resolution is therefore required to make a unique identification possible.

Apart from the requirement for a new, high angular-resolution, γ-ray telescope for the more precise location of known COS-B γ-ray sources, there is also a need for another instrument that can be used in a search for the γ-ray emission from specific X-ray-emitting objects. There are many objects in the current catalogues of X-ray sources in both the low energy (1–10 keV) and high energy (10–200 keV) ranges. If there is to be any hope of relating γ-ray emission to specific candidate X-ray objects, then an angular resolution of typically a few minutes of arc is required to resolve adjacent sources in crowded regions of the sky such as the galactic centre. High angular-resolution γ-ray telescopes would also be valuable in the observation of some extragalactic objects. For example, recent studies of the structure of the radio emission around a number of active galaxies have provided evidence for the ejection of material at relativistic velocities. X-ray emission from some such jets has been detected. It would also be interesting to map these objects in γ-radiation. Gamma-ray emission from the strong radio object Centaurus A has been reported by Hall *et al.* (1976). The intensity of the power-law spectrum (0.13–12 MeV) and the nuclear line emission at 1.6 and 4.5 MeV suggest that the peak luminosity of this object occurs at low γ-ray energies.

There has been a considerable effort to improve the angular resolution of track-chamber telescopes, particularly with the Gamma-Ray Observatory (GRO) mission in mind. This has involved making refinements to the wire spark-chamber system successfully used on the SAS-2 and COS-B missions. An alternative technique based on the use of drift chambers to locate the electron tracks with greater precision has also been developed (McKechnie *et al.* 1979). A comparison between these techniques is shown in figure 1, along with an indication of what the limiting performance is for an idealized drift chamber system. There is an intrinsic limit to the angular resolution of a track chamber that uses the electron trajectory information to determine the incident photon direction. The angular uncertainty gets larger at lower energies where the photon flux is higher. From this figure it is clear that arc-minute level resolution is technically impossible except for the very rare, highest energy, photons.

For energies close to 1 MeV telescopes have either used collimators to restrict the field of view or have made use of the kinematics of the Compton scattering process to determine the direction of the incident photon. Observations by the Rice group (Hall *et al.* 1976) were made with a collimator having a half angle of 15°. The MISO results were obtained by using a secondary fine collimator which provided a full-width half-maximum of 2.5° (Baker *et al.* 1979). Both Herzo *et al.* (1975) and Graml *et al.* (1977) have developed Compton telescopes based on the use of two multi-element detector planes in which they detected a Compton scattered event. This latter type of detector with a limiting angular resolution of 1–2° at a few megaelectronvolts has been selected for the GRO mission.

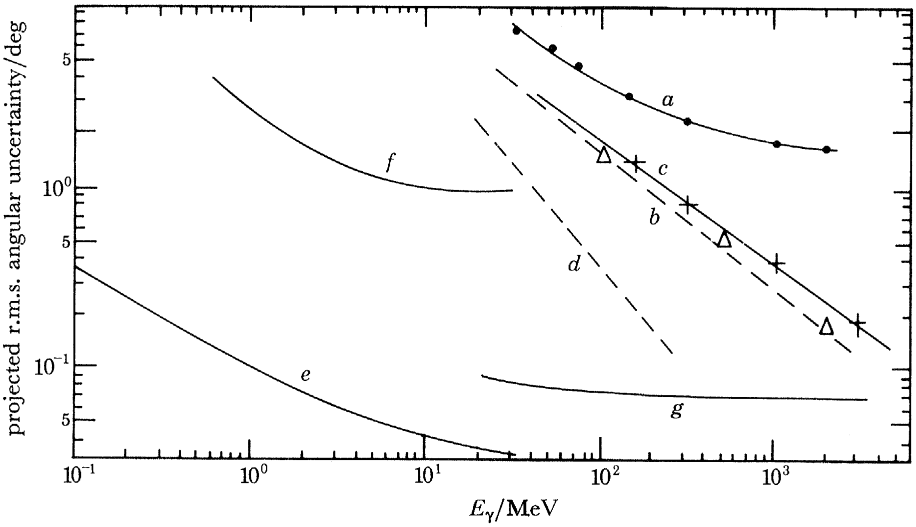

FIGURE 1. A comparison of the angular resolution of some γ-ray telescopes: (*a*) COS-B (beam calibration); (*b*) high energy telescope for GRO; (*c*) drift chamber telescope (beam calibration); (*d*) predicted limiting resolution for an ideal drift chamber; (*e*) low energy imaging telescope; (*f*) the Comptel telescope for GRO; (*g*) a drift chamber with coded aperture.

The value of applying coded aperture techniques in a high angular resolution telescope for X-ray astronomy has been demonstrated by Proctor *et al.* (1978). This work is a development of ideas presented earlier by Mertz (1965), Dicke (1968) and Ables (1968), some of whom had forseen the value of this technique at high photon energies. Recently there has been renewed interest in using this technique in γ-ray astronomy. Proposals have been made to use a coded aperture in conjunction with a drift chamber telescope (Ramsden 1979; Carter *et al.* 1980*a*) and a spark chamber (Prilutsky 1979) for high energy γ-ray astronomy, and with a position-sensitive sodium iodide detector (Carter *et al.* 1980*b*) for photons having an energy of about 1 MeV. All of these techniques are based on established position-sensitive detection systems, and the new feature is simply the addition of the mask. The deconvolution of the data obtained by using such a mask is also well understood.

A practical telescope for astonomy at high energies has been described (Carter *et al.* 1980*a*), which incorporates a 40-plane drift chamber essentially similar to the one that had been constructed by the authors. In this, the event selection is controlled by a time-of-flight scintillation counter telescope, a calorimeter and signals from associated anticoincidence detectors. The coded aperture requires the use of an absorber having a thickness equivalent to two or three radiation lengths. It is completely enclosed within an anticoincidence counter to veto γ-rays produced by interactions in the absorber. To maintain a reasonable field of view, the cell size of the mask will need to be about the same as the mask thickness (*ca.* 8 mm) and so, if the mask were to be positioned about 2.5 m above the drift chamber, an intrinsic angular resolution of 10′ could be achieved. The actual angular resolution should in fact be better than this by a factor that depends on the significance of the source flux. It has been shown that after a few hours of exposure such a telescope should be capable of locating the strongest of the COS-B sources to within a few minutes of arc and that the position of all the 29 COS-B sources could be found to this precision in a seven-day Spacelab flight.

At low energies, an imaging telescope could be constructed by making use of position-sensitive detectors initially developed for use in medical physics. These detection elements consist of a long bar of inorganic scintillation material treated in such a way as to attenuate the light, exponentially, as it passes to two photomultiplier tubes optically coupled to each end of the bar. The positional resolution varies along the bar and depends on the attenuation length for light along the detector. Studies have been made to optimize this parameter to ensure that the response is as uniform as possible while at the same time preserving the best energy resolution for the detector. Monte-Carlo simulations of the response of the detector have also shown that the degradation in the positional response is dominated by the variance in the number of photoelectrons generated in the photomultiplier tubes, and that effects caused by the range of Compton electrons are unimportant.

The theory of optimal coded masks indicates a preference for masks based on particular element patterns; for example 7 × 9, 15 × 17, 31 × 33. The choice of pattern and the number of bars in the detector plane is therefore influenced by the positional resolution along these detector elements. The positional resolution for a 660 keV photon in a 50 × 5 × 5 (cm^3) sodium iodide bar has already been shown to be better than ± 1.0 cm. This will permit a 7 × 9 element mask to be used and the detector plane would then consist of about 20 parallel bars. If the mask, which would contain four complete patterns, were placed 4 m in front of the detector plane, the basic angular resolution of the imaging telescope would be 15′ × 45′ at 600 keV. This again will be improved still further if the source is detected with a confidence level higher than the 99 % assumed in these calculations.

The use of such an imaging system in low energy γ-ray astronomy is of particular importance since it will then be possible to observe, simultaneously, the source and the inevitable background flux. This will mean that many of the systematic errors previously introduced by the difficulty of subtracting background will be avoided. Apart from this very significant benefit, which is hard to quantify, a telescope of the proportions indicated should have a sensitivity many times greater than that of existing telescopes.

The development of such imaging telescopes for use in future γ-ray astronomy programmes should enable a unique contribution to be made in this field. It would also raise the techniques of γ-ray astronomy to a level comparable with those that exist at other wavelengths.

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