

Rotating modulation collimator imagers

D.M. Smith ^{a,*}, G.J. Hurford ^b, S.E. Boggs ^c

^a *Department of Physics and Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA 95064, USA*

^b *Space Sciences Laboratory, University of California Berkeley, Berkeley, CA 94720, USA*

^c *Department of Physics and Space Sciences Laboratory, University of California Berkeley, Berkeley, CA 94720, USA*

Abstract

Rotating modulation collimators (RMCs) are one member of a family of techniques for X-ray imaging that do not require focusing optics. Instead such techniques use opaque material to create temporal or spatial variations in the detected signal from a source from which its image can be reconstructed. We discuss the RMC imaging technique and its relation to other members of that family, its application for the Reuven Ramaty High Energy Solar Spectroscopic Imager, and potential future missions such as Cyclone, a proposed NASA Small Explorer mission, and GRIFFIN, a hybrid technology combining RMCs with focusing optics.

© 2003 Elsevier B.V. All rights reserved.

Keywords: X-ray and γ -ray telescopes and instrumentation

1. Introduction

Rotating modulation collimators have been used for many years for X-ray imaging for both solar and non-solar applications (Oda, 1965; Schnopper et al., 1968; Takakura et al., 1982; Lin et al., 2002; Hurford et al., 2002). A basic rotating modulation collimator (RMC) consists of a detector (which need not have any spatial resolution) located beneath a bigrid collimator, i.e. a pair of widely separated grids, each of which has a large number of parallel, periodic slits and X-ray opaque slats (Fig. 1). At any instant in time, the transmission of the grid pair viewing a given X-ray source is a periodic function of the source direc-

tion in the plane orthogonal to the slits. If the whole system is rotated about the collimator axis, the count rate detected from a point source will vary rapidly with time.

Fig. 2 shows how this modulation depends on the characteristics of the source. Broadly speaking, the frequency of the modulation is proportional to the radial offset of the source; the overall phase of the pattern depends on the azimuthal position of the source; and the amplitude of the modulation is proportional to the total flux of the source. The modulation amplitude (but not the average signal) is reduced if the source size is not small compared to the angular resolution of the collimator (defined as one half of the ratio of the grid pitch to grid separation). As a result, the relative modulation amplitudes measured by grids with different resolutions provide information on the source size.

* Corresponding author.

E-mail address: dsmith@ssl.berkeley.edu (D.M. Smith).

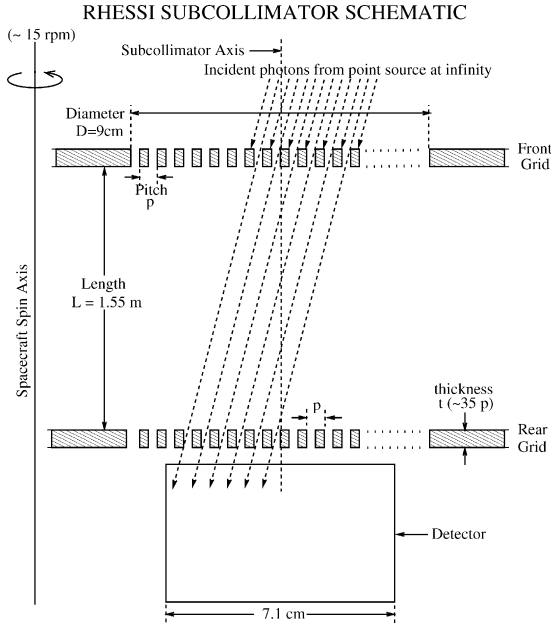


Fig. 1. Schematic of one subcollimator of the RHESI RMC.

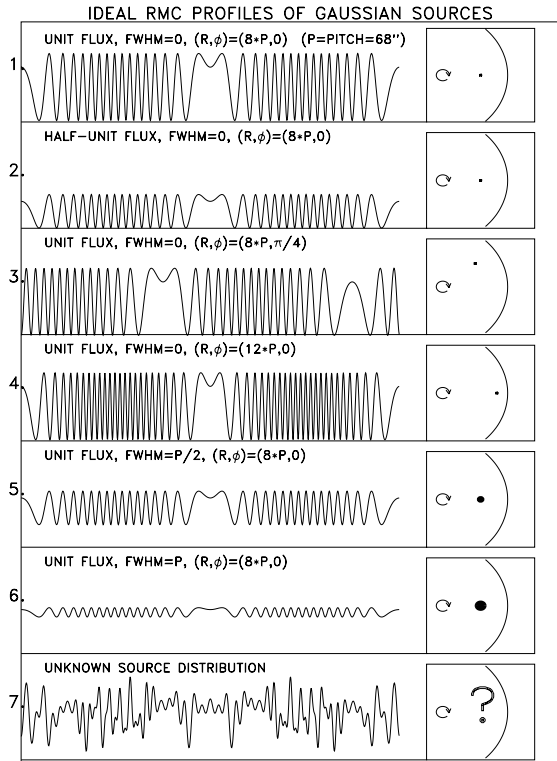


Fig. 2. The RMC principle: images and corresponding modulation patterns.

A more complex image gives a modulation pattern that is a linear superposition of the basic modulation patterns of its simpler components. Reconstruction of the complex image is then an inverse problem in which the goal is to determine the morphology of the source that gave rise to the observed signal. This problem is the precise mathematical equivalent to that in radio interferometry, where observed visibilities are used to reconstruct a source. The temporal modulation of the X-ray flux by an RMC is the counterpart of the visibilities obtained by correlating data in a radio baseline (Makishima et al., 1978; Prince et al., 1988). Both measure a set of Fourier components of the source distribution. Algorithms used in radio astronomy can be used in RMC imaging, including the CLEAN algorithm and maximum entropy. For discussions of these algorithms and other algorithms applicable to RMC image reconstruction see Hurford et al. (2002) and references therein.

2. Relation to other techniques

RMC imaging is part of a broad family of techniques, including coded-aperture imaging and pinhole cameras, that use selective blocking rather than focusing of rays (usually X-rays) to derive image information.

The most closely related approaches also use collimation by grids. They can be distinguished both by the number of grids employed and the technique used to temporally or spatially modulate the incident flux. SMM/HXIS (van Beek et al., 1980) achieved 8'' resolution with a direct imaging multigrad collimator in which there was a one-to-one correspondence between detector elements and image pixels. This approach results in a heavy loss of sensitivity and imposes significant alignment requirements.

Bigrid systems that do not require rotation to temporally modulate the X-ray flux have been designed for balloon applications, e.g. GRID (Orwig et al., 1989). In this case individual grid pairs exploit pointing jitter to produce quasi-random modulations. As long as the pointing is known to high precision, imaging is possible by

exploiting these modulations. Such a system is contemplated for GRIFFIN (see below).

Non-rotating bigrid collimators can also be used to spatially modulate (instead of temporally modulate) the incident flux. In this case the top and bottom grids have a slightly different pitch and the amplitude and phase of the resulting Moire pattern can be detected with a detector with only modest spatial resolution. A variation on this theme was used for solar imaging by the *Yohkoh* Hard X-ray Telescope (Kosugi et al., 1991), using pairs of subcollimators that differed in phase by 90° to measure specific Fourier components. Non-rotating bigrid systems, whether employing temporal or spatial modulation, require multiple collimators with the grids mounted at various rotational angles in order to perform two-dimensional imaging.

Coded-aperture imaging, discussed elsewhere in this volume (Skinner, 2003), has a different set of advantages and disadvantages. It uses a pseudo-random set of apertures in a single plane to cast a distinctive shadow in the detector plane. In analogy with RMCs, the angular resolution is given by the ratio of aperture diameter to grid-detector separation. In this case, however, the spatial resolution of the detectors must be commensurate with the aperture size, a constraint that limits the potential angular resolution. This is particularly relevant at γ -ray energies, since there is a fundamental limit on the pixel size: the energetic electrons released in the detector by Compton or photoelectric interactions require a finite distance to come to a stop. Thus arcsecond angular resolution would require an extremely large instrument. On the other hand, the coded mask removes only 50% of the source photons rather than the nominal 75% removed by an RMC (RMCs can be made with narrower slats than slits, increasing the throughput, but at the expense of the imaging performance).

Single grid systems have also exploited rotation. For example, Durouchoux et al. (1983) described a variant called the Rotating Modulator, which consists of a single set of parallel rotating bars above an array of detectors with modest spatial resolution. The throughput is the same as for a coded mask (50%) but the rotation allows

more independent measures of the image to be made by each detector element. A related example is the Gamma-Ray Imaging Payload (GRIP) (Althouse et al., 1985), a balloon instrument that used a rotating coded mask to help eliminate systematic errors due to uncertainties in detector calibration.

3. RHESSI

The highest angular resolution achieved to date in the hard X-ray and γ -ray regimes has been from RHESSI, a NASA Small Explorer mission launched on February 5, 2002, which uses a set of nine RMC subcollimators with different grid pitches to make images from 3 keV to several MeV (Hurford et al., 2002). All the grids are made of tungsten, except the finest, which is molybdenum. Each grid pair is viewed by a large, coaxial germanium detector. With 1.55 m between the top and bottom grids, grid pitches from $34\ \mu\text{m}$ to 2.75 mm give angular resolutions from $2.3''$ to $3'$. Despite the high angular resolution, RHESSI's pointing needs to be controlled to only $\sim 0.2^\circ$. This relaxed requirement is set by the 1° field of view, which is determined by the internal shadowing of the thick slats within each grid and the requirement that the shadow of the top grid mostly overlap the bottom grid. The pointing requirement is not driven by the angular resolution since precise aspect *knowledge* can be substituted for precise aspect *control*. Mechanical requirements also benefit from precise aspect knowledge in that only the relative twist of the front and rear grids needs to be accurately maintained (in this case to about an arcminute).

RHESSI's 15 rpm rotation rate means that full image quality can be achieved on timescales as short as 2 s. This is important since flare conditions evolve with time. RHESSI's images show bremsstrahlung from both thermal and non-thermal electron populations, separable by energy. They have already been studied (e.g. by Gallagher et al. (2002)) in conjunction with simultaneous images from other missions (which show thermal plasmas only) to study the behavior of energetic electrons in flares.

Two grids (with 35" and 3' resolution) are thick enough to be effective above 1 MeV, and have, in fact, produced the first sub-arcminute image ever made at these energies: an image of the 2.223 MeV line from neutron capture on protons in the X-class solar flare of July 23, 2002 (Hurford et al., 2003). Surprisingly, the nuclear γ -ray image was significantly displaced from the hard X-ray and γ -ray images of electron bremsstrahlung in the flare. Since the different energy ranges are imaged simultaneously through the same grids, the potential for systematic errors in image coalignment is discounted.

Although flares are usually signal-dominated, good pre-flight and in-flight calibration of the grids, coupled with the inherent ability of RMC's to suppress systematic errors, has contributed to the ability to make images in cases where the signal to background ratio is less than 1%.

4. Cyclone

The success of RHESSI suggested the possibility of a mission using similar technology but optimized for cosmic (i.e. faint) sources in the hard X-ray range. Cyclone (Boggs et al., 2000) is the resulting design, which has been proposed to NASA for its Small Explorer program. Cyclone uses much thinner germanium detectors enclosed in an anticoincidence shield made from an inorganic scintillator, to dramatically reduce the instrumental background. This very low background, combined with the robust resistance of the RMC technique to random or slowly periodic background variations, promises extremely high sensitivity in Cyclone's energy band (approximately 3–200 keV).

Cyclone will produce images down to 10" with an expected energy resolution of 550 eV at 78 keV. Among its major objectives will be a map of the Cas A supernova remnant in the 68 and 78 keV lines of ^{44}Ti , with different images at different velocities.

5. GRIFFIN

Gorenstein and Finoguenov (1994) first suggested putting an RMC in front of a crude imaging

optic. The temporal modulations from the RMC would provide the high-resolution imaging information, and the optic would concentrate the photons onto an extremely small detector, with negligible background. Two of us (DMS and GJH) are part of a team that has recently revived this idea (which we call GRIDs Followed by FocusING, or GRIFFIN) and proposed to NASA to build a test system with the eventual goal of a Medium-class Explorer mission. Angular resolution of 1" in the hard X-ray range could be achieved, which is about an order of magnitude better than the best results from grazing-incidence multilayer optics alone (Hussain et al., 1999). Using a single-reflection conical optic instead of the usual double-reflection quasi-Wolter I optic would compensate for most of the photons lost in the RMC, giving a comparable throughput per unit area to instruments like the hard X-ray telescope (HXT) planned for Constellation-X (Harrison et al., 1999). The energy range of GRIFFIN, like HXT, would be limited by the performance of grazing-incidence multilayer optics to something below 100 keV.

Acknowledgements

RHESSI is supported by NASA contract NAS5-98033.

References

- Althouse, W.E., et al., 1985. In: Proceedings of the 19th International Cosmic Ray Conference, vol. 3, p. 299.
- Boggs, S.E. et al., 2000. SPIE 4140, 166.
- Durouchoux, P. et al., 1983. A.&A. 120, 150.
- Gallagher, P.T. et al., 2002. Solar Phys. 210, 341.
- Gorenstein, P., Finoguenov, A., 1994. SPIE 2280, 11.
- Harrison, F.A. et al., 1999. SPIE 3765, 104.
- Hurford, G.J. et al., 2002. Solar Phys. 210, 61.
- Hurford, G.J. et al., 2003. Ap. J. Lett. 595, L77.
- Hussain, A.M. et al., 1999. SPIE 3766, 184.
- Kosugi, T. et al., 1991. Solar Phys. 136, 17.
- Lin, R.P. et al., 2002. Solar Phys. 210, 3.
- Makishima, K. et al., 1978. In: Van der Hucht, K.A., Vaiana, G. (Eds.), Proceedings of the 20th COSPAR meeting. Pergamon, Oxford, p. 277.
- Oda, M., 1965. Appl. Opt. 4, 143.

- Orwig, L.E., et al., 1989. In: Max '91 Workshop 2: Developments in Observations and Theory for Solar Cycle. vol. 22, p. 143.
- Prince, T.A. et al., 1988. *Solar Phys.* 118, 269.
- Schnopper, H.W. et al., 1968. *Space Sci. Rev.* 8, 534.
- Skinner, G., 2003. This volume.
- Takakura, T. et al., 1982. In: Proceedings of the 13th International Symposium on Space Technology and Science. AGNE, Tokyo, p. 1597.
- van Beek, H.F. et al., 1980. *Solar Phys.* 65, 39.