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THE USE OF DIAMOND TURNED & REPLICATED WOLTER 1 TELESCOPES FOR HIGH SENSITIVITY X-RAY ASTRONOMY

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ABSTRACT

Following the success of Einstein, it is clear that telescopes of very large area (~10^4 cm^2) with angular resolution ($\lesssim 20''$) are needed for deep X-ray surveys and other observations. After a discussion of these objectives, which form the basis of the NASA LAMAR mission, the design & performance of a five mirror telescope is described. The system was studied for possible flight on Spacelab to undertake observations & to act as a prototype module for LAMAR. Both diamond turning & replication methods of mirror production are discussed. The performance of a single Wolter I telescope with diamond turned mirrors will be described.

INTRODUCTION

Many astronomical objectives require ~100 times larger collecting area & a broader spectral sensitivity than have been available with Einstein. These requirements cannot easily be achieved with a single telescope, & thus the idea of an array of co-aligned telescopes has arisen. This concept, the Large Area Modular Array of Reflectors (LAMAR), is in NASA plans as a future space observatory. When operating as a free-flyer, from the Shuttle or from a Space Platform, a LAMAR observatory can obtain sensitivities 10^2-10^4 greater than Einstein. The large effective area of the LAMAR will thus allow spectral & time variability studies of faint sources. Recently, there has been some debate[1,2] on the choice of X-ray optics for LAMAR. The work described here is directed towards fabricating & flight testing a single LAMAR telescope unit, utilising Wolter I X-ray optics which are capable of achieving much higher angular resolution than the Kirkpatrick-Baez optics previously proposed for this mission[3]. In addition, during a Spacelab mission, this High Resolution LAMAR (HRL) telescope could undertake observations with sensitivity & high energy response substantially exceeding the capabilities of Einstein.

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SCIENTIFIC POSSIBILITIES

While the ultimate value of a LAMAR X-ray telescope will be realised by mounting it on a free-flying satellite or space platform, several important objectives could be achieved in a 7 day Spacelab mission. For the five mirror telescopes described here these include: i) Deep Surveys of Normal Galaxies. The telescope can detect sources of $L_x > 5 \times 10^{39}$ erg s^{-1} at the distance of the Virgo cluster. Most normal galaxies should thus be detectable out to ~20 Mpc. The nearer of these galaxies can be mapped in detail. Thus the luminosity function of compact soft X-ray galactic sources may be extended over 4 decades. The diffuse X-ray emission from nearby galaxies including possible hot gaseous halos can also be studied & the X-ray properties of distant galaxies correlated with their optical structure. ii) Surface Brightness Distribution of Clusters of Galaxies. Measurements of cluster X-ray surface brightness & gas temperature allow the gravitational potential, & thus the mass distribution, of a cluster to be determined. The extended spectral range of the proposed telescope is well matched to the X-ray emission from most clusters & will lead to much improved measurements of the temperature distribution. Distant clusters are unlikely to be smaller than ~1′ at z > 1. Thus the angular resolution of the HRL (~30") is appropriate since it is of the utmost importance to distinguish 1\` sources (clusters) from point sources. iii) Deep X-ray Survey at High Galactic Latitudes. The Einstein deep survey fields reveal QSOs & stars. QSOs appear to contribute at least 30% of the 1-3 keV diffuse X-ray background. Further progress requires X-ray spectra of a wide range of QSOs & a large increase in the number of detected optically selected QSOs. A deep X-ray survey by the HRL will be invaluable in determining the degree of flattening of the quasar counts fainter than m_b ~20. and will of course reveal many stars & clarify the situation with regard to optical faint ′star′ counts. iv) Study of Active Galaxies. X-ray emission from active galaxies seems to originate near the main site of energy release. Thus, investigation of the X-ray emission from active galaxies, QSOs & BL Lac objects provides an effective way to study the energy source. The variability of such sources restricts the size & efficiency of the emitting region, & spectral changes relate to emission & absorption mechanisms. An extended sky survey should reveal an increasing number of low redshift active galaxies & help relate their observed characteristics to those of QSOs. v) Galactic Studies. Large areas of the Galaxy can be viewed with intermediate sensitivity by restricting the viewing time per field. For example, about 500 square degrees could be mapped with the HRL to a sensitivity of ~10^{-2} UHURU units in ~3 days. This would reveal many X-ray stars & thus extend the stellar X-ray luminosity function to fainter objects.

TELESCOPE DESIGN & PERFORMANCE

The major components of the HRL X-ray telescope, shown in Fig. 1, include a nested set of 5 grazing incidence mirrors, a two position

Table 1 - HRL Mirror Assembly Parameters

		Radius (cm)				
		Paraboloid		Hyperboloid		
Mirror Number	Aproximate Grazing Angle (deg.)	Entrance	Exit	Entrance	Exit	Surface Material
1*	1.72	44.53	43.46	43.23	39.97	Ni
2	1.57	40.71	39.74	39.53	36.54	Ni
3	1.43	37.02	36.13	35.94	33.23	Ni
4	1.29	33.46	32.66	32.48	30.03	Au
5	1.16	30.01	29.29	29.14	26.94	Au
6+	1.03	26.68	26.04	25.91	23.95	Au
7*+	.91	23.47	22.91	22.79	21.07	Au
8*+	.79	20.38	19.89	19.78	18.29	Au
9*+	.67	17.39	16.97	16.88	15.61	Au
10*+	.56	14.51	14.16	14.08	13.02	Au

Focal length	360 cm
Paraboloid Length	36 cm
Hyperboloid Length	36 cm
Thickness of Center Support Plate	3.8 cm

*Indicates the five mirrors to be fabricated for HRL. The array has been designed for future addition of the other five mirrors. + Replication candidate.

Table 2 - Example HRL Observing Plan for a Single Spacelab Mission

Observational Objective	No. of Point-ings	*Duration of each Pointing	Limiting Sensitivity of each Pointing (UHURU Counts)	Total Observing Time for each Objective (Hours)
Map 1° x 4° of M31 Repeat 3 times	12	5 x 10^3	2 x10^{-3}	16.7
Map 4° x 4° of SMC	16	10^3	5 x 10^{-3}	4.4
Observe 3° x 3° in Virgo Cluster	9	5 x 10^3	2 x 10^{-3}	12.5
Deep Survey 1° x 1° at high latitude	1	4 x 10^4	10^{-3}	11.1
Survey 8° x 8° at high latitude	64	400	10^{-2}	7.1
Study 4 active galaxies	4	5 x 10^3	2 x 10^{-3}	5.6
Survey 5° x 5° of the Galactic Plane	25	400	10^{-2}	2.8

Mission total - 131: Pointings - 60 Hours

*The longer observations need not be contiguous but may be interrupted by earth occultations, etc.

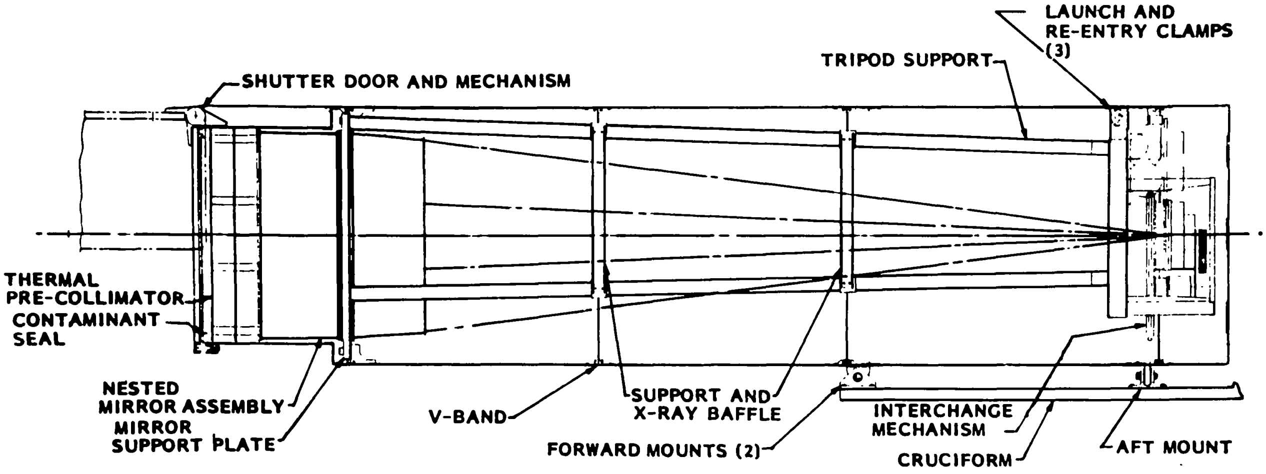

Fig 1 Schematic Diagram of the HRL Telescope

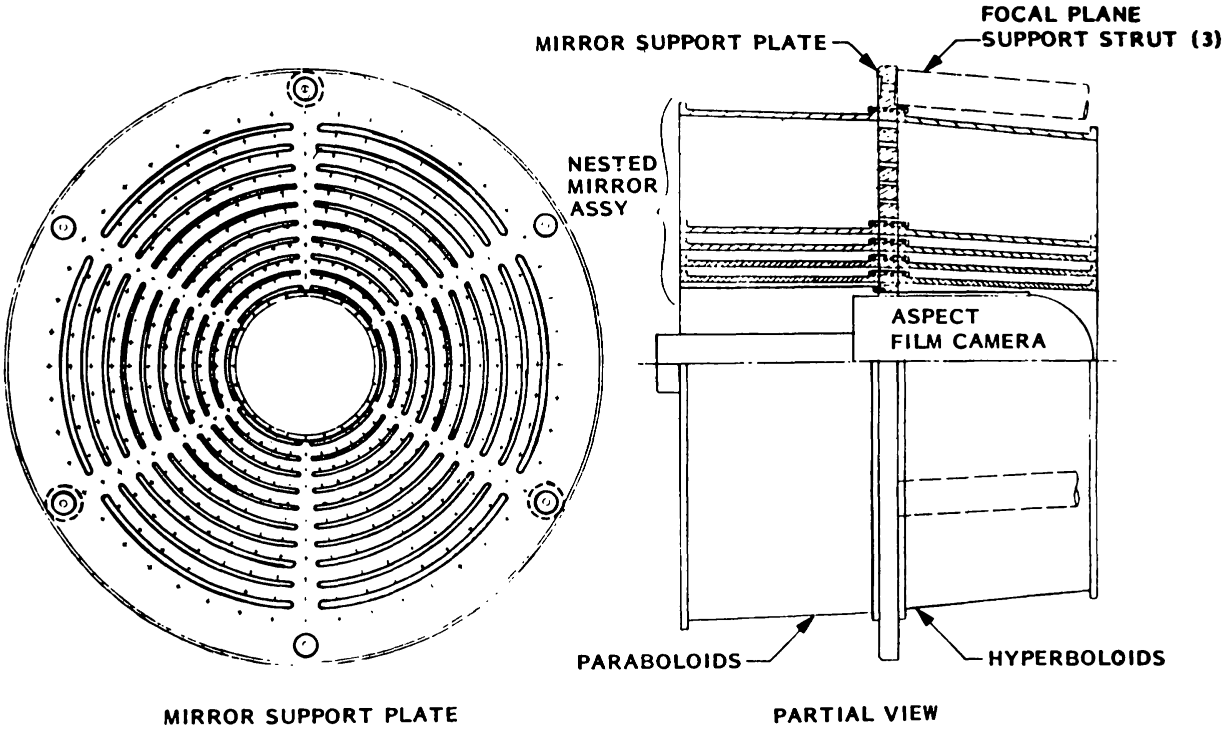

Fig 2 HRL Mirror Assembly. Views in the plane of the Mirror Support Plate and of a Partial Assembly cross section are shown.

rotary interchange mechanism to locate one of two Imaging Proportional Counters (IPC) at the telescope focus, a mechanical supporting structure and electronics for power, command & data handling. A 35 mm film camera will photograph the star field every 3 minutes during a 7 day mission. The telescope requires a pointing control such as the Spacelab IPS or equivalent. The HRL has a focal length of 3.6 m & a geometrical area of 500 cm^2 with the capability of expansion to 1350 cm^2 (10 mirrors). It fits within the length of two Spacelab pallets.

The mirror assembly involves a nested set of 5 mirrors (Fig 2). A center support plate holds these mirror elements in alignment, attaches to the outer payload cylinder & provides support for the focal plane assembly via a tripod. The assembly is designed to have its center of gravity in the plane of the support plate. Provision has been made to accommodate the 10 mirror array, but only the 5 mirrors studied are shown in Fig. 2. Parameters of the full ten mirror array are listed in Table I.

Fig. 3 shows the effective area for both the 5 mirror HRL & the 10 mirror telescope as a function of X-ray energy. In Fig. 4 the rms blur circle radius calculated for both the 5 mirror & 10 mirror systems, as a function of off-axis angle is shown at X-ray energies of .3, .85 & 2.5 keV. These plots are for an image 3 mm forward of the on-axis focal point which provides improved resolution at the edges of the telescope field.

The form of the mirrors is shown in Fig 2. The mirror blanks will be fabricated from rolled ring forgings of 5083 aluminium alloy which has been used successfully in an X-ray telescope[4] flown on an Aries rocket in October 1980. Precision measurements of the mirror figure, taken before & after vibration tests, the rocket launch & parachute recovery, indicate that no measurable distortion occurred from vibrational stress relief. Preliminary analysis of data from the calibration of this telescope at the 1000 ft test facility at Marshall Space Flight Center indicates that its image blur has a radius (FWHM) of less than 15 arc sec. A 25 second observation of Cygnus X-1 supports this result (Fig. 5).

The required paraboloid & hyperboloid figures on the interior of the mirror elements are to be directly machined in the aluminium substrates by diamond turning. The mirrors will be lapped & polished on a vertical axis lapping machine[5]. Valuable experience has been gained from polishing the Aries mirrors. It is clear from micrographs of the Aries paraboloid that the polished surface, over nearly the complete area is virtually structureless, which indicates that surface roughness is no more than 1 nm in amplitude (peak to peak). Some of the smaller mirrors could be made by replication as was done for the EXOSAT mirrors (de Korte, These proceedings). This would offer a major advantage in producing a complete LAMAR. Candidates for replication are indicated in table I.

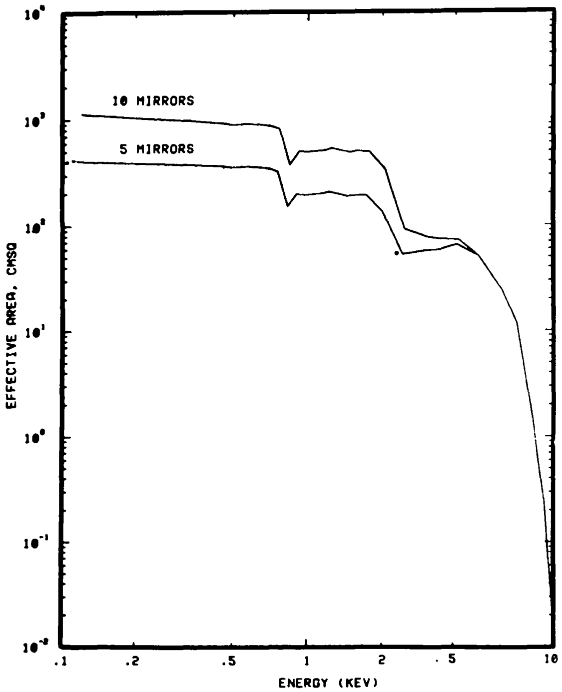

Fig 3 Calculated Effective Area for 5 and 10 Mirror HRL Array.

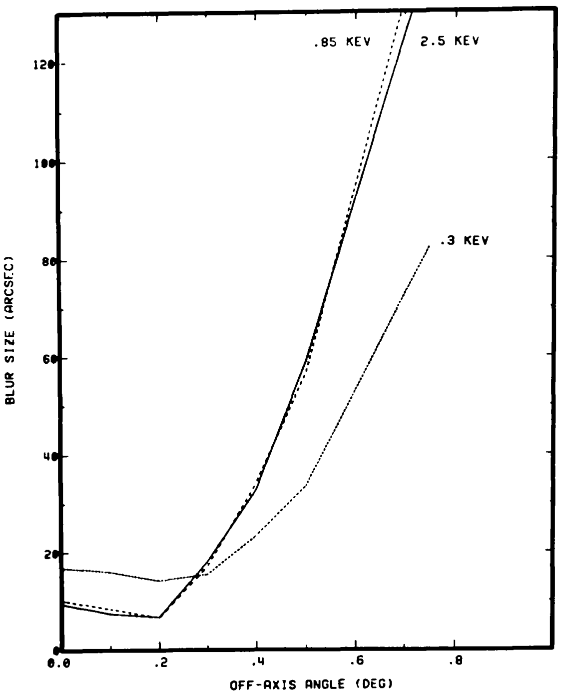

Fig 4a Blur Circle Radius for the 5 Mirror HRL Array.

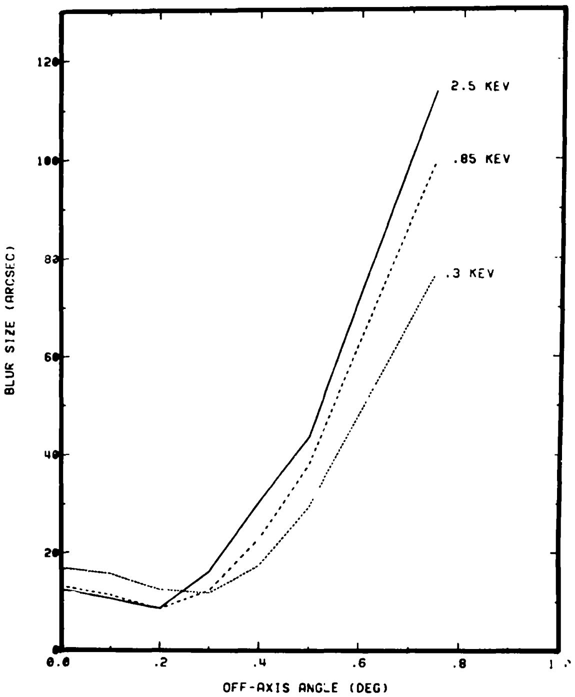

Fig 4b Blur Circle Radius for the 10 Mirror HRL Array.

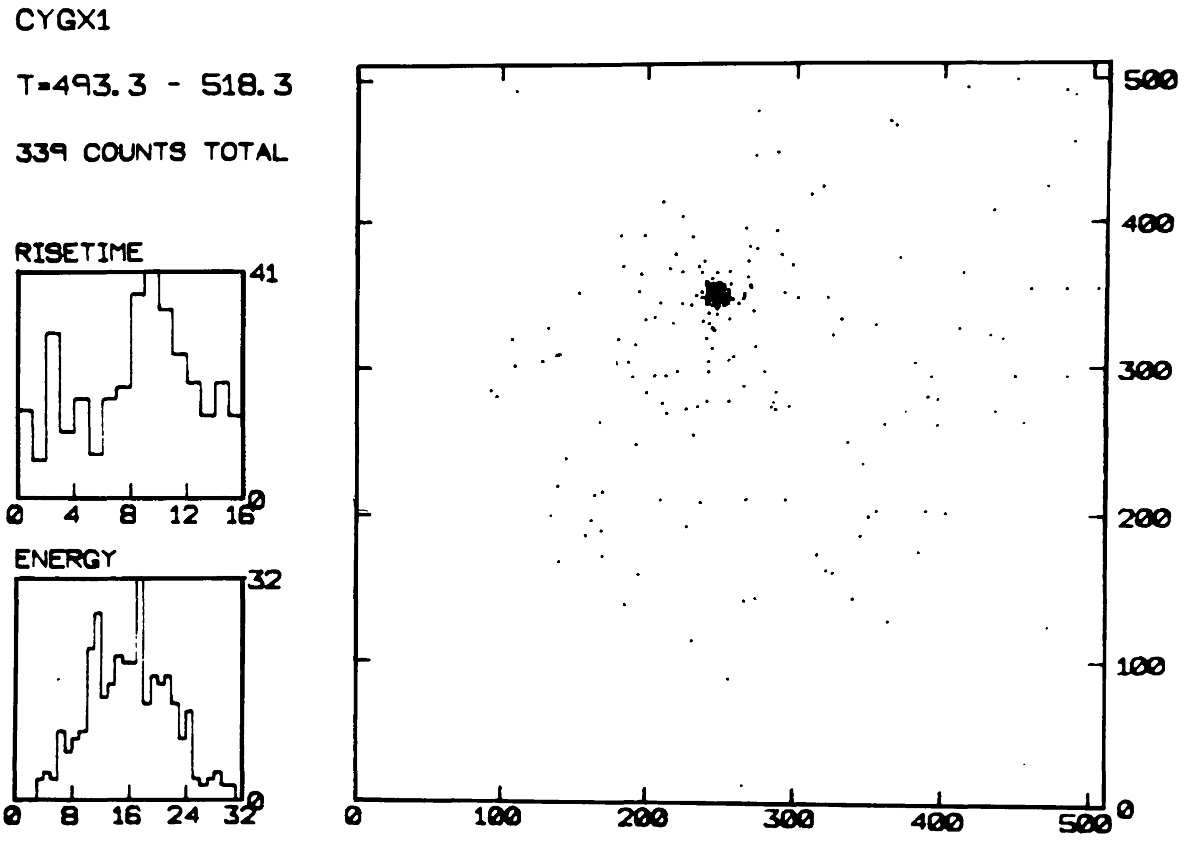

Fig 5 Image of Cygnus X1 obtained with a one Mirror WOLTER I Telescope flown on a NASA ARIES Rocket in October 1980.

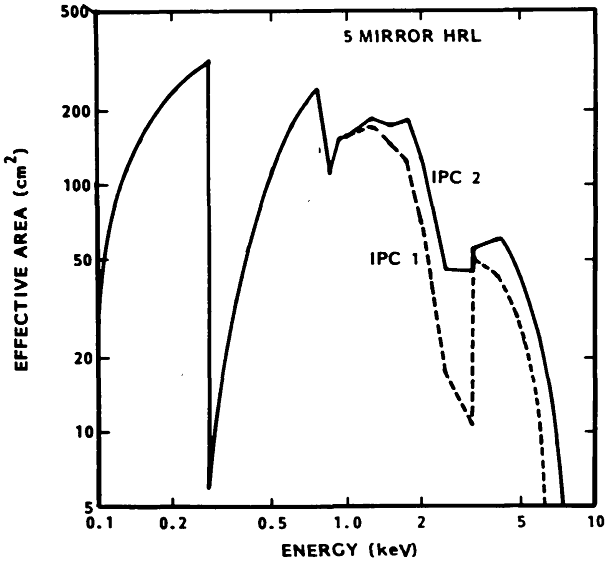

Fig 6 Effective Area includes Detector Efficiency for the 5 Mirror HRL Array.

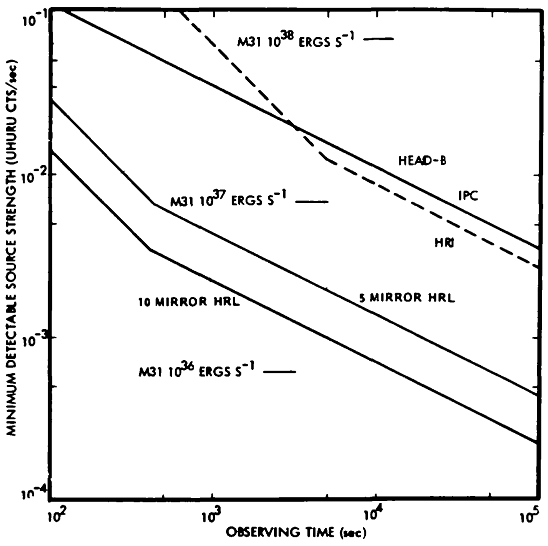

Fig 7 HRL 5 and 10 Mirror Telescope and Detector Sensitivities compared to the EINSTEIN IPC and HRI Figures.

The focal plane assembly consists of two imaging proportional counters (IPCs) mounted on a rotary interchange mechanism. Two IPC detectors are required to cover the full energy range of the HRL, with IPC 1 operating from 0.1-2 keV & IPC 2 sensing the range from 0.6-6 keV. These two detectors also provide a measure of redundancy because their energy range can be adjusted by a changing high voltage.

Effective area as a function of energy for the 5 mirror HRL telescope, including the IPCs, is shown in Fig. 6. The HRL has approximately twice the effective area in the 0.5-2 keV range as the IPC on the Einstein Observatory. Its response also extends to higher energy, having a cut-off at ~6 keV. In addition, IPC 1 can achieve ~3 times better angular resolution than its counterpart on Einstein thereby increasing the telescope sensitivity by a factor of 3.

Fig. 7 shows the sensitivity of the HRL for point sources compared with that of Einstein[6]. An optimum cell size for detection of faint point sources of 1 square arc min has been assumed. The source spectrum used was thermal with KT = 4 keV & a low energy photo-electric absorption cut-off of 0.3 keV ($N_H \sim 5 \times 10^{20}$ cm^{-2}). The above source spectrum, producing 1.7×10^{-11} ergs/sec from 2-6 keV (1 Uhuru c/sec), has been folded through the instrument response functions to obtain a counting rate, C, of 2 c/sec in the HRL. For comparison C = 1 c/sec for the Einstein IPC & 0.1 c/sec for the Einstein high resolution imager for the same input spectrum. Assuming 5 counts are necessary for detection in the signal limited case and 5 sigma above background for background limited observations, (the HEAO-B summary uses 3 counts & 3 sigma) the data of Fig. 7 have been calculated from $M = 5/CT$ (signal limited) & $M = 5 \sqrt{B/C} \; \sqrt{T}$ (background limited) where M is the minimum detectable source strength in Uhuru c/sec, C is the detector counting rate, B, is the background rate & T the observing time. The luminosities for sources in M31 have been placed on the graph by taking the same source spectrum as above for the normalizing 2-6 keV range & placing it at 670 kpc to determine the strength in Uhuru c/sec. Fig. 7 indicates that the 5 mirror HRL can achieve a sensitivity in ~2000 sec for which the instruments on Einstein need 10^5 sec. The 10 mirror HRL achieves this same sensitivity in ~400 sec, before becoming background limited.

A sample observing plan for a 7 day Spacelab mission is outlined in table 2. It assumes the Spacelab pointing system is under HRL control for 50% of a 7 day mission (84 hours) & that for 70% of this time (60 hours) useful observations may be conducted. Use of the pointing system allows decoupling of the HRL observations from the orbiter attitude. This leads to a distinct advantage over instruments fixed to a pallet which must interleave their observations with the orbiter time line.

The HRL capability during a 7 day Spacelab mission may be illustrated by comparison with time required for the Einstein Observatory to perform the observations in Table 2. Einstein would require three months to carry out the Table 2 observing plan at the HRL sensitivity level while for the ten mirror HRL, the time required is more than a year.

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