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THE LAMAR:

A HIGH THROUGHPUT X-RAY ASTRONOMY FACILITY

FOR A MODERATE COST MISSION

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1.0 INTRODUCTION

Large collecting power is essential for many of the objectives of future programs of X-ray astronomy. In order to carry out astrophysical investigations directly in X-rays, a minimum number of photons must be obtained. It is evident that good angular resolution is needed to recognize and image diffuse sources, obtain precise positions, reduce background, and avoid confusion. The specific role of the high throughput instrument is to collect a sufficient number of photons from sources, both point-like and extended, to permit an in-depth study of individual objects and group properties to be accomplished within a reasonable time without the limitations of background, confusion, and shot noise. The studies include: measurements of fluxes and luminosity functions, studies of morphlogy and imaging of low surface brightness features, temporal variations, and spectral properties. To achieve a good measurement of these parameters, e.g. to characterize a temporal variation in quantitative terms or measure a temperature gradient with precision, the measurements must of necessity be made at a high level of significance, typically tens of σ, which is well beyond that merely required to establish the existence of a source.

A value for effective area that represents a reasonable goal for future high throughput imaging instruments is about 10^4 cm^2. This is approximately 50 times that of the Einstein Observatory and 10 times AXAF. A reasonable goal for the angular resolution is about a minute of arc (diameter of circle containing 50% of the power). With this combination of large area and angular resolution, this instrument would be unique in capability when compared to all other mission concepts under study. The Large Area Modular Array of Reflectors (LAMAR) is a practical approach for achieving this desired combination of large effective area and good angular resolution. For imaging purposes, the sensitivity of an array of identical modules (imaging telescopes and detectors) is equivalent in every respect to that of a single long telescope with the same total aperture and angular resolution. Given the appropriate manufacturing technology for mass production, the array of modules are much easier and less costly to fabricate than a monolithic telescope. There is no need for precise co-alignment of the modules. Furthermore, the modular approach results in more efficient use of the available volume on any spacecraft because the viewing aperture can be the large area side of the spacecraft.

In the discussion of scientific objectives and estimated performance, the name LAMAR is used in a generic sense. It covers a number of technical approaches for both the mirrors and detectors, including several described at this workshop, that are capable of being made into an array of 10^4 cm^2. Different choices for the mirror and detector technology provide varying degrees of effective area, angular resolution, field of view, short wavelength response and energy resolution No one mirror-detector system is optimum in all respects. The key to low cost, namely remaining within the limits of a moderate cost Explorer mission, is adopting a single set of technologies for the mirrors, detectors, and dispersive elements, in particular technologies which are amenable to mass production methods at low unit cost. Also, the technique should not require so specialized skills or tools that there would be difficulty, irrespective of cost, of producing the required number of modules in a reasonable interval of time. A moderate cost approach is discussed in Sect. 4. In the discussion that appears in Sect. 2, a high throughput X-ray imaging instrument with energy resolution is shown to be an important tool for studying key problems in galactic and extragalactic astronomy. In so doing, the basic parameters assumed for the system are:

effective area (mirror): 10^4 cm^2 at 2 keV {50X Einstein, 10X AXAF}
2×10^3 cm^2 at 5 keV

resolution (50% flux diameter): 1 arcminute or better on axis

field of view: 1 degree

For objectives involving moderate resolution X-ray line spectroscopy ($E/\Delta E \approx 100$) the use of objective gratings is assumed, in particular, reflection gratings forward of the mirrors as discussed in Sect. 3.

LAMAR is unique with respect to any other mission under discussion. Its combination of large collecting area and good angular resolution is not paralleled by any past mission nor any future facility that is being planned. It collecting power represents an improvement over that of the Einstein Observatory, as well as that of EXOSAT and ROSAT, the next two telescope missions in X-ray astronomy, by about two orders of magnitude. With respect to future missions, it has an order of magnitude larger collecting power than AXAF, as well as facilities that are being discussed by the European Space Agency and Japan. LAMAR can address scientific objectives in many areas of both galactic and extragalactic astronomy. It is not restricted to the study of one aspect of X-ray sources nor to a single class of objects. It can obtain results on many objects in a time that is short compared to any other facility. Being able to obtain results in a reasonably short time is essential because many studies are simply impractical if the observer requires more than about two years to carry out his/her program. Thus, LAMAR can serve the scientific community in a very general way and can accommodate the needs of a very large number of users.

2.0 EXPECTED PERFORMANCE OF LAMAR

We consider the performance of a LAMAR in several hypothetical observations relevant to the fundamental problem areas of astronomy and astrophysics that were described in the theoretical presentations during the first day of this workshop. These areas are:

(1) Cosmology, the X-ray Background, and Large Scale Structure of the Universe

(2) Clusters of Galaxies and Their Evolution

(3) Quasars and Other Active Galactic Nuclei

(4) Compact Objects in Our Galaxy

(5) Stellar Coronae

(6) Energy Input to the Interstellar Medium

Examples are considered in each of these subject areas.

2.1 Cosmology

LAMAR can study the overall isotropy of the sky in the redshift range $z \approx 1$ to 3 by measuring the 2-4 keV background. By studying apparent volume density vs. z for several classes of extragalactic X-ray source, LAMAR may allow an independent estimate of q_0. Studies of evolution can be carried out by obtaining complete X-ray selected samples (with detailed X-ray information) of Seyferts, quasars, BL Lac objects and clusters of galaxies to redshifts $z \approx 0.5$ to 3. Features in the X-ray background may reveal large scale structures, and events associated with the initial formation of clusters or of galaxies in clusters.

The X-ray background above a few keV is free of galactic effects and offers the best chance to measure the isotropy of the universe over the entire sky on scales between 1 deg^2 and 12 hours, and in the redshift interval of $z \sim 1$ to 3 from which the bulk of the X-ray background probably originates. As pointed out by Fabian at this Workshop, the X-ray background is sensitive to the structure of the universe on a scale of 10-100 Mpc. The fundamental limit to measuring the isotropy arises from source confusion noise due to the X-ray source counts $N(> S) = 2.7 \times 10^{-16} \ S^{-3/2}$ $ster^{-1}$, where S = ergs/cm^2 s 0.3 to 3.5 keV. Focusing instruments are essential in order to eliminate individual discrete sources to as low a level as possible while integrating the diffuse background flux in the remainder of the field of view. In an observation of 2000 seconds, LAMAR can eliminate sources down to a level of 10^{-14} erg/cm^2 s. Scaling from measured background rates in the

Einstein Observatory, we estimate that in this time, about 6000 counts from diffuse X-ray background (2-4 keV) and 4 x 10^4 counts at most of non-X-ray background accumulate in 1 deg^2. Source confusion noise over the 1 deg^2 is expected to be 350 counts. Therefore, the total uncertainty due to statistical fluctuation is 7%. Systematic errors in the non-X-ray background can probably be reduced to 1%, therefore, the practical limit is about 10% for a single 1 deg^2 field. For those objectives requiring smaller uncertainty, the observation of many fields will reduce this uncertainty considerably. Measurement of $\sim 10^4$ independent fields would bring it down to 0.1%. This would be feasible in several years of LAMAR operation, and would occur naturally in the course of normal observing. Such precision is essentially unobtainable with an instrument having less area.

Based upon LAMAR's high throughput and its ability to study many sources, it is possible to define various cosmological tests. For example, it has been pointed out that the apparent volume density vs. redshift depends on q_0 more strongly than the classical tests of apparent optical magnitude or apparent size vs. redshift.[1] At that time only clusters of galaxies were known to be ubiquitous extragalactic sources. Now, we might apply the test independently to Seyferts or BL Lac objects. All of these classes have luminosity functions of roughly 10^{-7} Mpc^{-3} for $L > 10^{44}$ erg/s. Although redshifts would have to be obtained by optical means, the power of LAMAR is that the samples can probably be defined completely based purely on X-ray properties, e.g., finite spatial extent for clusters of galaxies, a power law spectrum of index 0.5 to 0.6 for Seyferts (cf.

Mushotzky et al. 1980),[2] and a soft X-ray excess and time variability for BL Lac objects. To detect ~100 objects in a range of $\Delta z = 0.1$ at $z = 1$ requires 1000 fields of 1 deg^2 observed for 2000 sec each. The LAMAR sensitivity will be to 10^{-14} erg/cm^2 s, or $L = 10^{44}$ erg/s, in this time. Of course, any such measurement of cosmological parameters must simultaneously address the possibility of source evolution. Use of the classical $\langle V/V_m \rangle$ test will prevent us from being fooled, even if the test were inconclusive. However, in X-rays we have a unique possibility of deconvolving the evolution because of the rigorous constraint of not exceeding the X-ray background.

2.2 Clusters of Galaxies and Their Evolution

The results of the Einstein Observatory have confirmed our expectations based upon previous results that X-ray observations are an important source of new information concerning clusters of galaxies. Clusters of galaxies are easily identified in X-rays as a diffuse source with kT above 2 keV. The X-ray picture of clusters may exhibit considerable structure. In fact, the X-ray signature of a cluster of galaxies is so characteristic that new clusters of galaxies will probably be found much more easily in the future by X-ray measurements than by optical.

The Einstein Observatory was able to study relatively nearby clusters. It established that there exists a diversity of morphological types (cf., Forman and Jones, A.R.A.A. 1982).[3] A surprising preponderance of clusters with complex structure and asymmetry was found in comparison to clusters with more smoothly distributed gas, such as the Coma Cluster. Subsequent optical measurements have tended to show that the distribution of galaxies is indeed correlated with the increases in X-ray surface brightness as in Abell 2069.[4] As explained below, X-ray measurements are potentially a good method for mapping the distribution of mass within a cluster, as well as for determining the total mass of clusters. However, the Einstein Observatory did not have the throughput required to map the temperature and temperature gradient of the cluster gas. Thus, it could not provide much direct information pertaining to the measurement of cluster masses and their distribution inside the cluster. While the Einstein Observatory produced important results on the morphology of several dozen individual clusters, its sample of distant clusters was too small for results on cluster formation and evolution to be conclusive.

The Einstein morphological studies reveal clusters of different ages, at the current epoch (cf. Forman and Jones 1982).[3] We would like to study clusters of different age at a variety of cosmological epochs back to $z = 1$. It is not obvious a priori what is required to perform the morphological study. From an examination of the Einstein X-ray images, it seems that clusters with 5 x 5 pixels above the 3σ contour and with a peak contour of at least 10σ significance can be qualitatively classified. With an estimated 3/4 to 1 arcmin resolution, a 10^4 second LAMAR observation will give a morphological picture of a cluster to redshifts of $z = 0.2$ ($L_x \geq 3 \times 10^{43}$ erg/s), $z = 0.5$ ($L_x \geq 10^{44}$ erg/s) and $z = 1.0$ ($L_x \geq 3 \times 10^{44}$ erg/s.

LAMAR is the key instrument in this regard because clusters of galaxies are extended X-ray sources and moderate angular resolution is adequate for carrying out many of the objectives. Figure 1 is an X-ray contour plot of Abell 2069 as observed by the Imaging Proportional Counter of the Einstein Observatory.[4] In addition to the three principal condensations, LAMAR would see gas of much lower surface brightness. Superimposed upon this diagram is a 1' x 1' grid representing cells in which temperature could be measured. Simulations indicate that in 10^4 seconds of observing time the temperature could be measured in each of those cells to an accuracy of better than 10%. A2069 is at $z = 0.12$. At 2 or 3 times this distance, according to certain models of cluster evolution, we should be able to detect systematic differences in luminosity, morphology and temperature distribution between those objects and the relatively nearby clusters, and thus detect the manifestations of cluster evolution.

<u>Mass of Galaxies and Clusters of Galaxies</u>

Under conditions of hydrostatic equilibrium hot gas will be distributed in a gravitation potential according to the expression:

$$-kT_{gas}/G\mu M_H \left(\frac{d\ \text{Log}\ \rho_{gas}}{d\ \text{Log}\ r} + \frac{d\ \log\ T_{gas}}{d\ \log\ r} \right) r = M\ (r)$$

Thus, measurements of local temperature, the temperature gradient, and the density gradient will provide a good determination of M(r), the total mass interior to r. The result is rather unambiguous if the condition of isothermal equilibrium can be established. Galaxies in clusters, particularly if they

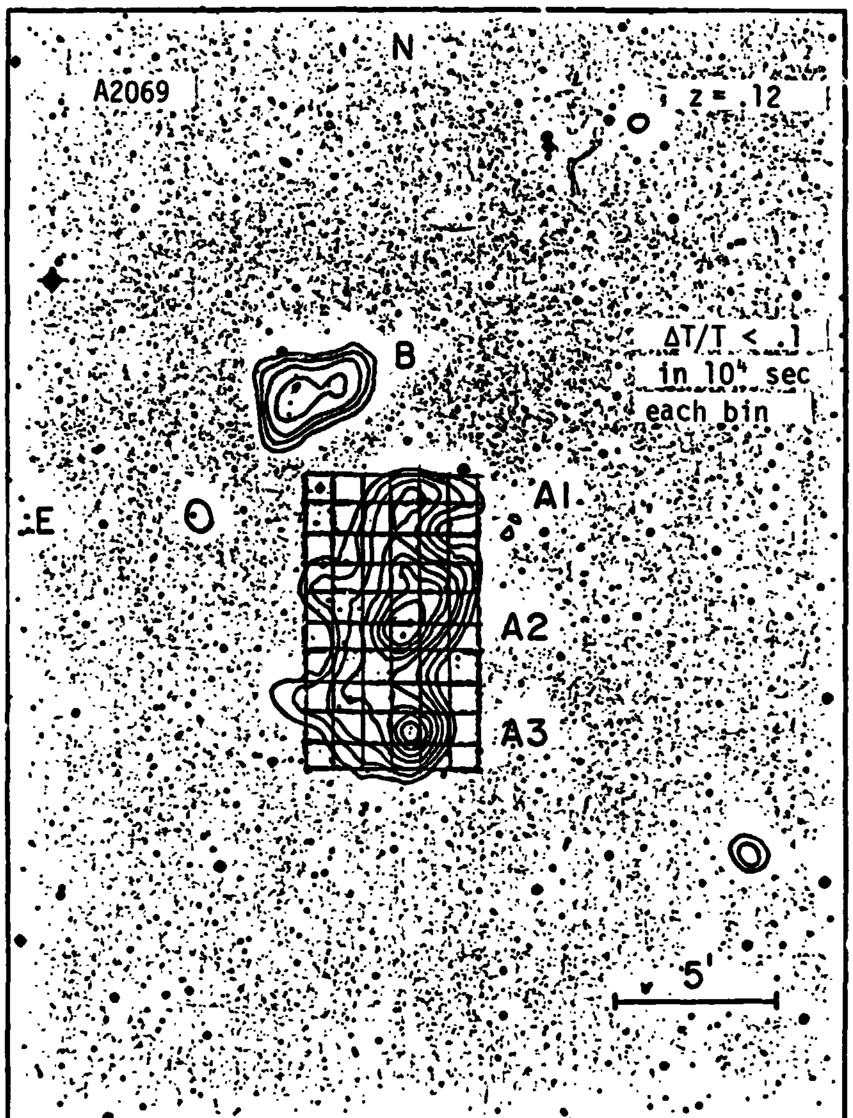


Figure 1

are relatively stationary such as M87 in Virgo, are in a position to have gaseous halos and can be expected to be in a condition of hydrostatic equilibrium. With the Einstein Observatory, it was possible to measure a mass of M87.[5] A LAMAR would have 50X the effective area of the Einstein Observatory (even more above 3 keV) and thus much better capability for measuring temperature and temperature gradients. Consequently, it will be able to determine masses for many more galaxies. With these results, we can study the relations between dark and luminous matter for galaxies of various types and in various environments.

By the same method, the total masses of clusters of galaxies and groups of galaxies can be studied with LAMAR. This is beyond the capability of the Einstein Observatory because of the rapid fall of its effective area above 3 keV. As kT of many clusters are typically 5-8 keV, good response in that energy range is needed to measure temperature gradients and consequently to derive their masses.

Large Scale Structure of the Universe

One of the important objectives in astronomy is to study the structure of the universe on various size scales and to search for other clustering hierarchies. There is reason to believe that X-ray measurements will prove to be very useful for this study. A. Fabian has pointed out at this workshop that diffuse X-rays may be the best probe of the universe in the range 10-100 Mpc. The factor of 50 larger throughput of LAMAR compared to the Einstein Observatory and even more above 3 keV will enable it to examine regions of much lower surface brightness which extend further from the cluster center. In principle, this will permit the search for structure on a larger scale than clusters.

As X-ray measurements (> 2 keV) are so specific to extragalactic objects, LAMAR is expected to find a large number of new extragalactic objects. The distribution of some category or sub-category may exhibit a structure or clustering hierarchy that is not apparent in visible light against the optical background of stars and normal galaxies. For example, the tendency to form superclusters may be more apparent in the correlation or lack thereof between regions of diffuse X-ray emitting gas than in galaxies.

Structural features of large scale may be evident in studies of the X-ray background. Recent papers suggest two possible mechanisms that may indeed result in larger scale structure. A 100 Mpc void has been reported in Bootes (Kirschner et al. 1981).[6] If the X-ray background is linearly proportional to total mass along the line of sight out to the Hubble distance of say 4000 Mpc (i.e. the sum of all active galactic nuclei and possible hot gas), then a 100 Mpc void would be detectable as a diminution in the X-ray background over the entire 1° field.

$$\frac{100 \text{ Mpc}}{4000 \text{ Mpc}} = 0.025$$

Source confusion noise may make it impossible to detect an effect of this amount in any one field but the observation of many fields should be revealing of structure of this magnitude. Another possible source of variations in the X-ray background has been suggested by Ostriker and Cowie.[7] In their picture, the agent of galaxy formation is multiple supernova explosions in the ambient gas occurring at the epoch $z = 5$. The process of galaxy formation in the intergalactic medium is analogous to that of star formation in our own galaxy. A consequence of this process is the creation of hot cavities; $T = 10^{8}$K, with a diameter of 15 Mpc. Their surface brightness is about 2×10^{-8} ergs/cm^{2}-sec-ster (i.e., equal to the isotropic background) and angular size about 15' to 30'. This should lead to significant variations in the X-ray background within the LAMAR $1^{\circ} \times 1^{\circ}$ field of view that are easily detectable. The Einstein Observatory, as well as EXOSAT and ROSAT, do not have sufficient throughput above 2 keV to detect variation in the extragalactic X-ray background.

2.3 Quasars and Other Galaxies with Active Nuclei

One of the significant features of X-ray measurements is their specificity for extragalactic objects for data above 2 keV in energy and above 20^{o} in galactic latitudes. In that regime, X-ray images are dominated by point-like active galactic nuclei and the diffuse emission of clusters of galaxies. In particular, measurements by LAMAR would result in finding a large number of new quasars. Optical observations would still be needed to determine redshifts, but the selection process based upon X-ray characteristics would make that a relatively straightforward and routine procedure as the sample should be relatively free of galactic objects. The key point about LAMAR is that it would allow studies and classification of quasars according to their X-ray characteristics, such as luminosity, spectral index, and possible X-ray emission or absorption lines, and temporal behavior. Large throughput is needed to obtain a level of significance much beyond that required to merely establish existence.

Temporal Behavior

The study of temporal variations promises to be a very important diagnostic tool for active galactic nuclei as described by A. Lightman at this symposium. There are theoretical reasons to believe and considerable observational evidence to indicate that active galactic nuclei will exhibit fast time variations in their X-ray flux. LAMAR is essential for observing temporal variations in all but the few very brightest and nearest objects. Imaging is necessary for removing background and avoiding source confusion. Figure 2 is a simulation of a type of temporal variation expected to occur often in a QSO[2] (c.f. Lightman) if the energy source is accretion onto a black hole. A QSO of

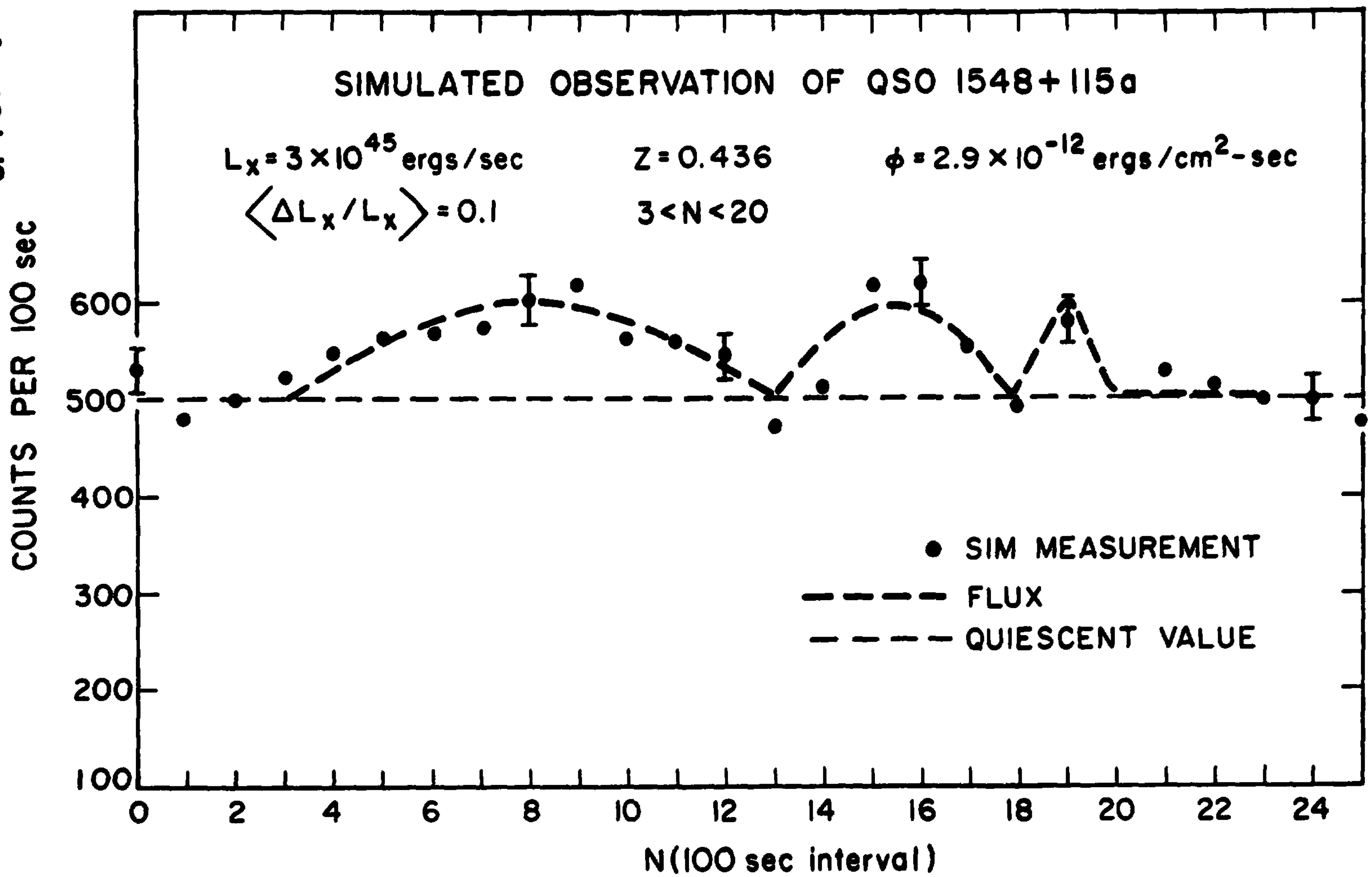

SIMULATED OBSERVATION OF QSO 1548+115a
$L_X = 3 \times 10^{45}$ ergs/sec
Z = 0.436
$\phi = 2.9 \times 10^{-12}$ ergs/cm^2-sec
$\langle \Delta L_X / L_X \rangle = 0.1$
3<N<20
COUNTS PER 100 sec
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
18
20
22
24
N(100 sec interval)
SIM MEASUREMENT
FLUX
QUIESCENT VALUE

Figure 2

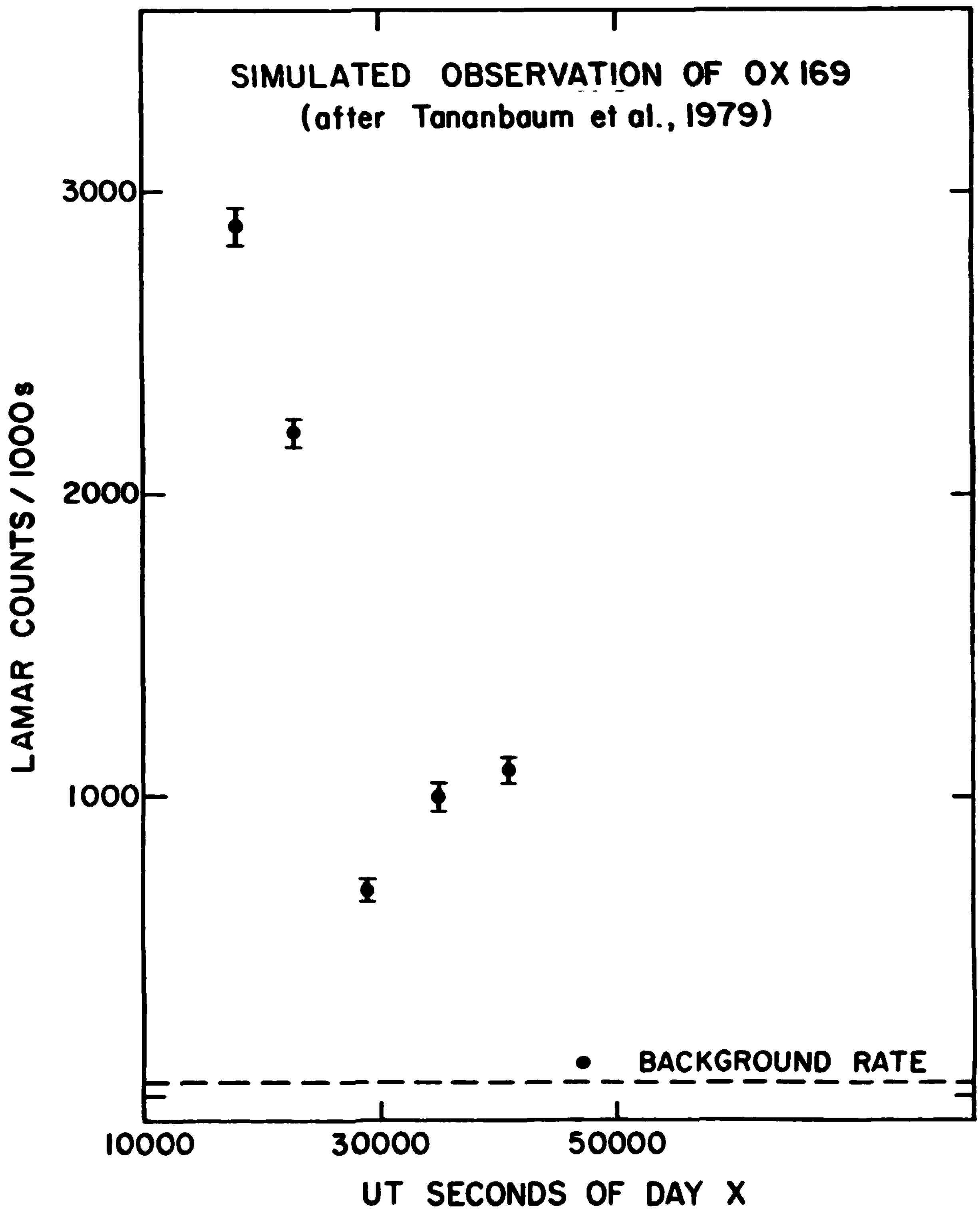

SIMULATED OBSERVATION OF OX 169
(after Tananbaum et al., 1979)
3000
2000
1000
LAMAR COUNTS / 1000s
BACKGROUND RATE
10000
30000
50000
UT SECONDS OF DAY X

Figure 3

moderate X-ray intensity has been selected for simulation. Sinusoidal periods of decreasing length correspond to a series of three final orbits around the nucleus. A more spectacular temporal variation is simulated in Figure 3. This is based on an actual Einstein Observatory measurement of a faint quasar in which only 47 counts were obtained. There is an indication of large variability in a short time.[8]

The coupling of spectral measurements to temporal will provide even more diagnostic information about the environment surrounding an active galactic nucleus. There is evidence from a combination of Ariel 5 and Einstein Observatory data for systematic correlations between the total X-ray emission from Seyfert galaxies and the ratio in flux between a soft (0.5-1 keV) and a harder component (2-10 keV) (Elvis and Lawrence 1981).[9] Variable intrinsic absorption of soft X-rays plays a role in the correlation. LAMAR will be able to carry out spectral/temporal studies in detail for many objects.

2.4 Compact Objects in the Galaxy

One of the great contributions of X-ray astronomy to astrophysics is the discovery of close binary systems containing compact objects that exhibit a remarkable range of time variations of intensity. These systems present an opportunity to study the behavior of neutron stars and other compact objects in an environment where they are accreting substantial streams of matter. The X-ray Timing Explorer (XTE) will be undertaken as a dedicated low cost mission to study these systems using large area non-imaging detectors. While XTE is expected to produce significant results based upon observations of the hundred or so most intense galactic objects, we can already anticipate the need for follow-on investigations with a more sophisticated instrument that can deal with fainter objects. With its imaging capability and large area, LAMAR will be able to observe much fainter objects because background effects and source confusion are eliminated. Thus, it can address a variety of new systems such as neutron stars in other environments, as well as cataclysmic variables containing degenerate dwarfs.

Neutron Stars

The greater sensitivity of the LAMAR extends the scope of neutron star investigations considerably by increasing the number of channels of observation. They are described below.

(1) Compact Objects in Supernova Remnants

A number of supernova remnants have been shown by the Einstein Observatory to contain compact X-ray emitting objects. These include W50 (SS433), G109-1, RCW103, the Vela SNR, and others. Although this collection of objects represents a mixture of X-rays from accreting binary systems, synchrotron acceleration of particles and hot neutron star surfaces, they are as a group rather young neutron stars. They may present aspects of neutron star behavior that are different than compact binaries which are generally much older objects.

(2) Radio Pulsars

The Columbia University group has detected X-ray emission from several radio pulsars with the Imaging Proportional Counter of the Einstein Observatory (Helfand 1981).[10] The objects seem to be spatially extended indicating that X-rays are produced as a result of active particle acceleration as in the Crab Nebula and Vela. Pulsars are isolated neutron stars and represent objects intermediate in age between those found in supernova remnants and those in compact binary systems. With 50 times the throughput of the Einstein Observatry, LAMAR shoould be able to study many pulsars.

(3) Possible Persistent X-ray Sources at Gamma Ray Burst Positions

Several models for gamma ray bursts (e.g. Woosley and Wallace)[11] predict that there will be persistent X-ray emission. There is marginal evidence for such a correspondence in an Einstein Observatory observation. If the fluxes are within an order or two of magnitude of predicted, then the catalog of precise gamma ray burst positions can be examined with LAMAR for a study of highly magnetized neutron stars.

(4) Faint Compact Binary Systems (Neighbor Galaxies)

The discovery of individual systems exhibiting a new type of behavior, such as Cyg X-1, Her X-1, and AM Her, has had a profound effect upon our perception and understanding of the physics of compact objects. Thus, the detection of additional objects with unique temporal behavior could have a great significance that is difficult to predetermine. The imaging capability of LAMAR will allow it to study much fainter compact binary systems whether they are within our own galaxy and of relatively low intrinsic luminosity or in neighbor galaxies where they are faint because of distance. Thus, LAMAR would make a considerably larger number of neutron star compact binaries accessible to study. While there is no reason to believe a priori that this larger group will contain phenomena or features that are not seen among the more intense group, the previous history of compact objects indicates that even a single object can have an impact that is revolutionary.

Cataclysmic Variables

In addition to compact binary systems containing neutron stars, there exists fainter objects containing degenerate dwarfs which includes cataclysmic variables (CV). Their time scales of temporal change are not likely to be as rapid but not necessarily less interesting. This means that with an imaging detector faint objects can be studied because we can integrate for longer periods of time without background or confusion becoming a factor. The recently discovered X-ray CV's (AM Her, 2A0311-227, V1223 Sag, H2237-035) show both optical and X-ray periodicities and quasi-periodicities which allow diagnosis of the structure and mass transfer in these systems.

As an example of how LAMAR will perform in the study of the temporal behavior of cataclysmic variables, we consider the faintest object that is likely to be of interest. As described by D. Lamb at this workshop, it is one that emits at 10^{31} ergs/sec at a distance of 1000 pc. There are hundreds of objects more intense than this. (More distant objects are difficult to study optically.) In LAMAR this source will count at a 0.5 cts/sec with essentially no background. We can easily study temporal behavior of individual flares on a time scale of 50 seconds or more. Search for periodicities and spectral changes will be accomplished quite easily. The spectral resolution of LAMAR will permit a study of correlated changes of soft and hard components.

2.5 Stellar Coronae

One of the major contributions of the HEAO program and the Einstein Observatory (HEAO-2), in particular. has been to establish X-ray measurements as a major diagnostic tool for stellar coronae. X-rays have been detected from stars of virtually every spectral type and flare activity has been found. Some moderate resolution line spectroscopy was obtained for the few most intense objects. As impressive as the Einstein Observatory results may be, they represent only the beginning phases of what could be a major new means of fundamental investigations of stellar coronae. The effective area of the Einstein Observatory telescope was only 200 cm^2. Because its effective area will be 50 times that of the Einstein Obervatory and 10 times that of AXAF, the LAMAR is a much more powerful tool for stellar photometry. With the use of more efficient dispersive techniques, LAMAR's increase of throughput over Einstein for moderate resolution spectroscopy ($E/\Delta E \approx 100$) is potentially even much larger than that for imaging and photometry.

It should be possible to make a grating that is at least 10 times as efficient as the objective transmission grating of Einstein. Reflection gratings, as discussed by W. Cash at this symposium, will allow much higher line densities and, consequently, much higher dispersions. The key point is that the dispersion would be large enough to make an Imaging Proportional Counter feasible as the detector of the dispersed spectrum. The IPC's efficiency is about four times higher than that of the high resolution imager of the Einstein Observatory. Hence, even if only a fourth of the full area of the LAMAR were devoted to spectroscopy, the increase in throughput relative to Einstein would be larger by a factor of:

$$50/4 \times 10 \times 4 \approx 500.$$

This would be a large enough increase to make moderate resolution spectroscopy applicable to many stellar objects. Assuming that 1/4 of the LAMAR's total area is devoted to reflection gratings and assuming that the grating efficiency is [illegible], the estimated count rate in the dispersed spectrum of a star emitting 10^{29} ergs/s at a distance of 25 pc is 0.5 counts/s in the 0.5 to 1.5 keV band. Thus, an observation of 2×10^4 seconds will provide some 10^4 counts, and a comparable number of background counts. For a resolution of 100, the average energy bin will contain 100 counts, and many of these will be in the form of lines so that many bins will contain several hundred counts. This is sufficient to provide meaningful measurements of temperature and ionization equilibria.

Photometry in conjunction with low resolution spectroscopy ($E/\Delta E \approx 2$) at 1 keV can be applied to many stars. This is useful for monitoring flare activity and detecting changes in temperature that are correlated with increases in intensity. Figure 4 is an illustration of the spectrum of a star at a distance of 40 pc emitting 10^{28} ergs/s as observed in LAMAR for a time of 10^4 sec. Spectra are shown for a pure thermal spectrum (Raymond & Smith) of kT = 0.17 keV, as well as for various amounts of an additional component flux with kT = 1.0 keV. There is no difficulty in detecting a small percentage of the higher temperature component. In the example taken, the star could be in the Hyades cluster. When the LAMAR is pointed to that region, we would expect that several stars would be observed simultaneously within the 1^{o} field of view of LAMAR.

The features of stellar coronae that could be studied with X-ray measurements have been discussed by Linsky at this symposium. They are:

Temperatures, range and dependence upon luminosity
Densities
Flow velocities
Total energy input and heating mechanism
Energy balance
Geometry, fraction of the volume filled by loops
Wind acceleration mechanisms
Interaction of winds with interstellar medium
Flares on stars of various types

The types of measurements needed to carry out these studies are:

(a) Imaging for measurement of flux with some spectral resolution (low resolution spectroscopy) to distinguish between soft and harder bands.

(b) Identification of new stellar sources with high

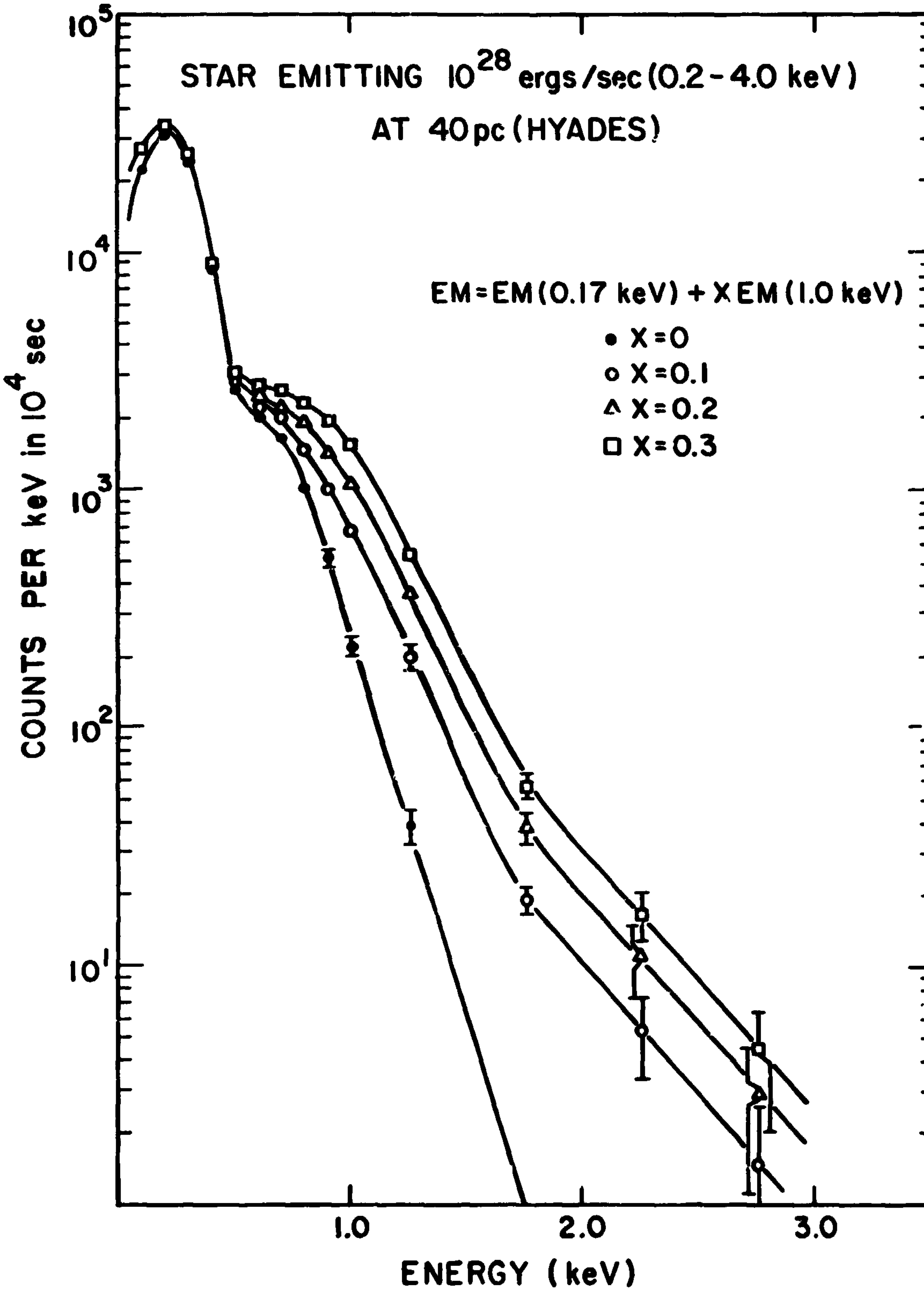

STAR EMITTING 10^{28} ergs/sec (0.2-4.0 keV)
AT 40 pc (HYADES)
EM=EM(0.17 keV)+X EM(1.0 keV)
● X=0
○ X=0.1
△ X=0.2
□ X=0.3
COUNTS PER keV in 10^4 sec
ENERGY (keV)
10^5
10^4
10^3
10^2
10^1
1.0
2.0
3.0

Figure 4

sensitivity providing the capability to obtain X-ray luminosity functions of various categories of stars.

(c) Temporal studies of flares and other activity, simultaneous temperature-flux measurements.

(d) Moderate resolution spectroscopy ($E/\Delta E \approx 100$).

(e) High resolution spectroscopy ($E/\Delta E \approx 1000$).

LAMAR will be able to provide measurement capabilities (a), (b), and (c) for many stars when used in its imaging mode. With the use of reflection gratings forward of the mirror assemblies over at least some of the mirrors (e.g. at 25% of the total area) it can provide (d), a moderate resolution spectroscopy capability. High resolution spectroscopy measurements will be out by AXAF. Thus, LAMAR will be able to address many of the areas of principal concern in stellar coronae.

2.6 Interstellar Medium

It has been established that a large fraction of the volume of the interstellar medium (ISM) contains a hot gaseous component of low density. The signature of this component is the soft X-ray background which is the predominant source of diffuse X-rays in the 0.1-0.3 keV band. Several years of sounding rocket measurements by the University of Wisconsin group have produced a soft X-ray map of the entire sky in $6^o \times 6^o$ bins. This map shows a highly structural gas that is perhaps within a hundred parsecs or so of the Sun. With the high throughput imaging ($\sim 10^4$ cm^2 effective area, 1' angular resolution, 1^o field) and its spectral ability which consists of low resolution

($E/\Delta E \approx 2$) spectroscopy for diffuse regions and moderate resolution spectroscopy ($E/\Delta E \approx 100$) for point sources, it is possible to carry out additional studies of the ISM that are relevant to the topics discussed by Cowie and Shull at this symposium.

(1) Imaging of the Galactic Component of the X-ray Background in Several Spectral Bands, 0.1-0.3 keV, 0.5-1 keV, and 1-2 keV.

Because of absorption within the plane of our galaxy, we detect higher energy X-rays out to larger distances. The 0.1-0.3 keV band is primarily local, up to 200 pc, the 0.5-1 keV band can reach out to 1000 pc, while the 1-2 keV band extends the reach almost to the galactic center. With the LAMAR, we have sufficient throughput to image the background on the scale of a fraction of a degree. The count rate in a 1° field would be 20 counts/s in the 0.1-0.3 keV band, on the average perhaps a factor of 3 lower in the 0.5-1 keV band, and another factor of 3 lower at 1-2 keV. (Above 2 keV the extragalactic component is dominant.) With integration times of 10^3 seconds or more for each 1° field, we would be able to construct surface brightness maps with considerable significance in each of the three energy bands on a scale of a fraction of a degree. We would detect the surface brightness variations that result from old supernova shells that are no longer identifiable as discrete radio sources. We would also detect diffuse regions that are heated as a result of stellar particle emission.

(2) Resolution of Discrete Sources Which Contribute to Heating of the ISM.

Resolving discrete sources is essential for identifying the residual diffuse component that represents the interstellar gas. Furthermore, it will lead to the identification of discrete objects that are significant sources of energy input to the ISM. Probable examples of the latter are the X-ray emitting OB stars and associations detected by the Einstein Observatory. In the η Carinae region and in Orion, there is circumstantial evidence for this process by the proximity of diffuse emission to a high density of discrete X-ray sources.

(3) X-ray Absorption Spectra as a Probe of the ISM.

Absorption features in the continuum spectra of discrete sources can be studied with the moderate resolution spectroscopy capability of the LAMAR. The LAMAR's high throughput will make these studies feasible for many objects by providing a probe of the galaxy along the many directions to fairly intense sources. We would detect the O and Ne edges of cold material and perhaps that of matter in a higher ionization state.

(4) Imaging of Old SNR's and Giant Bubbles.

Although these objects are of large diameter, good angular resolution is still required for imaging because of the need to resolve and remove numerous discrete sources. The hot component of the ISM is undoubtedly related to shock heating by old SNR's as described by Cox and Smith, McKee, Cowie, and Ostriker, among others. We should see the diffuse shells of old SNR's plus "giant bubbles" like the one found in the Cygnus region that may have originated from the interaction of multiple SNR's.[12]

(5) Studies of the ISM Neighbor Galaxies.

Our understanding of the ISM of our own galaxy will be greatly aided by images of neighbor galaxies, such as the LMC, SMC and M31. For the LMC and SMC, we will obtain a complete picture of the hot component of their ISM and the relation of the major spatial features to SNR's and other sources of heating.

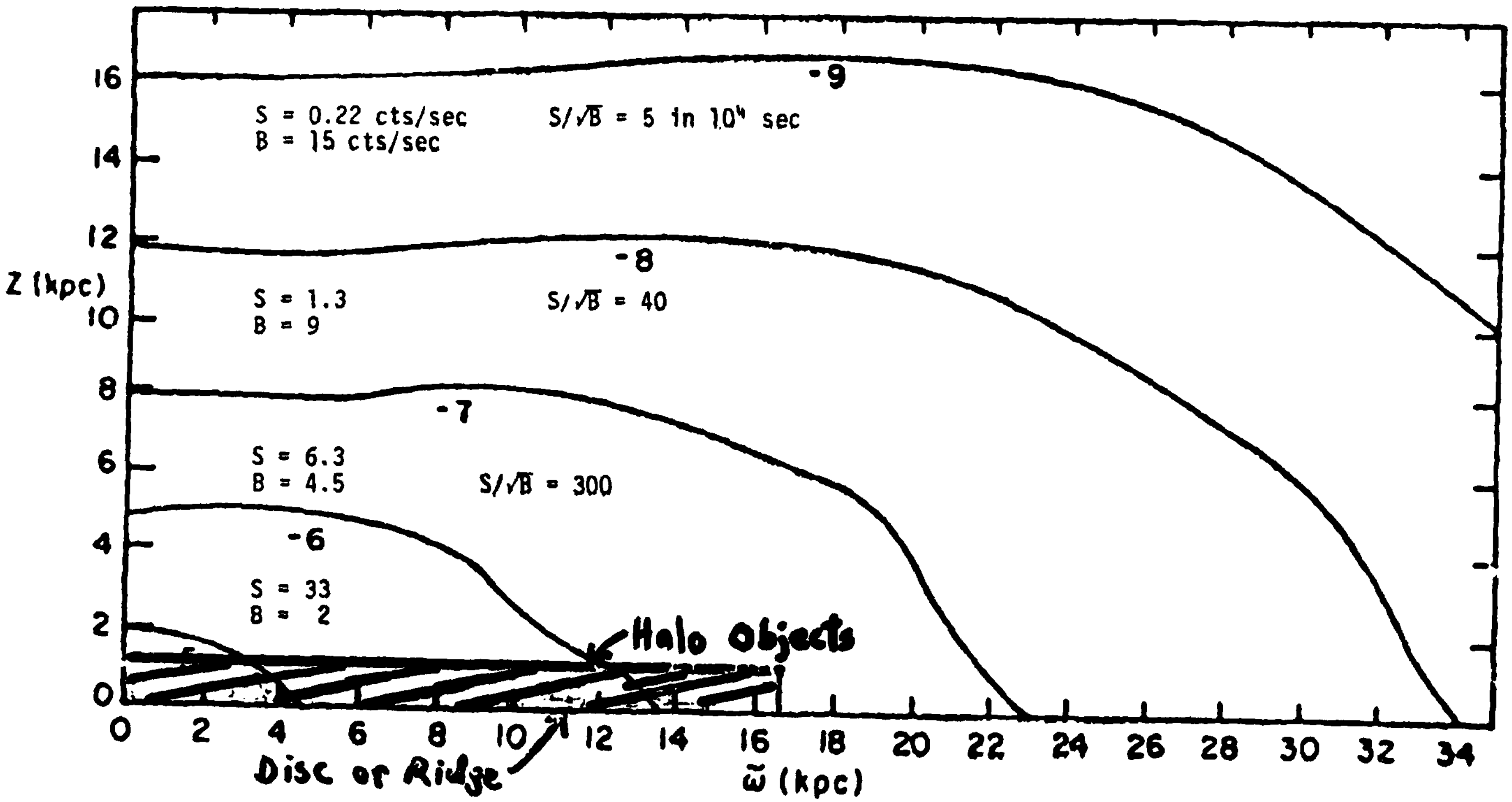
(6) Coronae of Normal Galaxies Within 3 Mpc.

The production of hot gas by supernova explosions and active stellar objects will lead to the establishment of a steady hot corona around normal galaxies. The corona is an integral effect of the heating processes. The features of the corona, such as its density, scale height, and relation to the plane, can be measured. There are theoretical calculations by Bregman,[13] which suggest that LAMAR should be able to measure the coronae of nearby edge on galaxies within a few Mpc. Figure 5 indicates the signal expected at various heights above the plane in an observation of 10^4 seconds.

3.0 HIGH THROUGHPUT SPECTROSCOPY WITH LAMAR

Requirements for high throughput are even greater for spectroscopy than for imaging. The existence of an X-ray source and even its position can be determined from relatively few photons. When background is negligible, 10 photons in the image are sufficient. However, to carry out spectroscopy studies, many

X-ray Coronae Around Galaxies
J.N. Bregman, Ap.J., 237, 681 (1980)
Model D
Edge On Galaxy at 3.3 Mpc   1' ~ 1 kpc



S = counts/sec from corona integrated over area between contours.
B = counts/sec from background integrated over area between contours.

Figure 5

more photons are needed. For example, if kT = 4 keV, simulations show that 4000 photons are required in order to determine a value for the temperature with ±10% precision by fitting model spectra to continuum data obtained with a telescope system having good response at higher energy, such as LAMAR or AXAF. (Without good response at 4 keV, the measurement takes much longer or cannot be done.) If the spectrum is a power law with -1.5 as the number-energy spectral index, in order to obtain ±10% accuracy in the spectral index, 500 counts are required if the spectrum is not self-absorbed ($N_H = 2 \times 10^2$), but the number of photons needed climbs rapidly as intrinsic absorption increases. At $N_H \approx 10^{22}$, which is not unlike several Seyfert galaxies studied, 10^4 counts are needed for a 10% precision in the spectral index measurement. Thus, for broad band spectral measurements, we require from a factor of 50 to 1000 more photons than for merely establishing existence. For dispersive line spectroscopy, the details of the discussion are different, but the general conclusion is the same; a large number of photons is needed to arrive at a quantitative result. For example, to measure temperature, we may need to determine the ratio of two lines to better than 10% precision. At least 200 photons are needed in each line. The counts in lines are generally only a fraction of the total number of incident photons. Taking the finite efficiency of the dispersive element into account, we conclude that the collecting area of the system must take in several hundred to several thousand total photons for line spectroscopy to provide a quantitatively meaningful result.

We consider two forms of spectroscopy that could be carried out by LAMAR. One is non-dispersive spectroscopy for gross spectral characteristics of sources dominated by continuum, temperature and temperature gradients in diffuse sources, such as clusters of galaxies, and spectrophotometry for faint and variable sources. These are carried out in conjunction with imaging. The other form of spectroscopy is a dispersive option that requires additional hardware.

3.1 Non-Dispersive Spectroscopy

For many faint and diffuse sources, there is no alternative to non-dispersive spectroscopy. In cases where lines are weak, such as quasars, non-dispersive spectroscopy may be the only form of spectroscopy that is feasible. As an example of non-dispersive spectroscopy in a diffuse source, we consider a measurement of the temperature distribution of the cluster A2069 in cells of 1' x 1' (Fig. 1). Simulations show that $>10^4$ sec are required for a measurement resulting in $\Delta T/T < .1$. The temperature gradient in combination with the surface brightness map could then be used to create a map of the mass distribution.

The detector for non-dispersive spectroscopy could be the imaging proportional counter. Recent devices provide as good an energy resolution as conventional proportional counters, $E/\Delta E \approx 5$ at 6 keV. With this level of energy resolution, it was possible for proportional counters aboard Ariel 5, OSO-8 and HEAO-1 to detect Fe lines in clusters of galaxies and spectral features in supernova remnants. Use of a scintillating imaging proportional counter as described by W. Ku[14] at this meeting and elsewhere and Anderson[15] could provide about twice as good energy resolution. This type of detector is still in the development stage, so it is not yet known what loss of spatial resolution is involved compared to an ordinary IPC or how reliable these detectors would be in long term operation.

3.2 Dispersive Spectroscopy

A paper presented by W. Cash at this meeting describes a method for dispersive spectroscopy by use of reflection gratings in the extreme off-axis configuration, forward of the mirror. The rulings are nearly parallel to the incident direction of the radiation. The reflection efficiency of the gratings are high, below 1.5 keV. Because the ruling density is high, 10^4 lines/mm, dispersions are large enough for an imaging proportional counter to be used as the detectors. A system with 1' of angular resolution would provide an energy resolution, $E/\Delta E$ of about 100 at 1 keV. As a LAMAR imaging system is compatible with the requirements of the reflection gratings, it is worthwhile to consider a combined imaging-spectroscopy LAMAR system. There are two possibilities. In one, every module has a dual function. Gratings would be placed before each mirror for spectroscopy measurements. When the gratings are removed, each module operates in an imaging mode. The second possibility is to have two types of modules, one for imaging, the other optimized for spectroscopy. The advantage of removable gratings is higher throughput as the full power of the LAMAR is available in any given observation whether the objective is imaging or spectroscopy. The advantage of the second configuration is simplicity, compactness, and no moving parts. Study is needed to determine which configuration is preferred.

Assigning reasonable values to the various efficiencies and obscurations, one can estimate that in the dispersive spectroscopy mode the LAMAR would have an effective area of about 10^3 cm^2. This is substantial and would permit dispersive spectroscopy to be carried out on many objects.

4.0 MODERATE COST APPROACH FOR LAMAR

Although the LAMAR is a large area facility, it can be developed with the cost constraints of a moderate mission. There are two considerations which mitigate the cost. One is the fact that the resolution goal is only about a minute of arc which allows a number of telescope manufacturing techniques to be feasible that would fail at the arc second level. For example, high cost figuring and polishing techniques are not required. The other factor is the modular construction of LAMAR. The problem of developing an array of large area reduces to one of finding a manufacturing technique that is efficient at making many copies of a module. Numerically controlled machines and computer assistance are two techniques that are useful in this regard. The module itself can be of optimum size with respect to problems of construction, testing, and integration. Furthermore, the modular approach has another cost advantage over a monolithic device in that it allows the essential elements of the system to be fully tested and understood from studies of one or a few sample modules. No "scale-up" problems, changes in technique, or other uncertainties arise when embarking upon the major phase of construction. One key to controlling costs is to use a single technology for each of the three items, mirror assemblies, detectors, and gratings.

At present, there are several technologies for the development of mirror assemblies that seem promising for LAMAR. To provide some credibility to the idea that LAMAR can be developed at moderate cost, we consider the particular techniques under study at the Center for Astrophysics for mirrors and detectors as an example. Our approach is based upon the construction of mirror assemblies consisting of nested plates of float glass with imaging proportional counters as detectors. The elements of this method are listed in Table 4-1. It is based upon the use of commercial materials and the avoidance of polishing for the reflecting surface. Numerically controlled machining and computer assistance are used for the formation of the figure.

4.1 The Mirror Assembly

The mirror assembly can be constructed of commercially available float glass with a gold coating. X-ray reflectivity is good at short wavelengths. Glass plates are constrained mechanically to form a figure that is almost parabolic. A nested system equivalent in size to one LAMAR module has been used successfully on a series of rocket flights.[16] The theoretical angular resolution of such a system is limited by elastic deformations in the bent plates. Several measures can be taken to improve the resolution as summarized in Table 4-2. Mechanical tolerances are expected to be important long before reaching the ultimate resolution of a pre-figured or "slumped" plate.

Table 4-1

MODERATE COST APPROACH FOR 10^2 MODULES FOR LAMAR

Nested Plate Mirrors	
Reflecting Surfaces:	Commercial float glass (Au coated) No polishing required
Figure Formation:	Automated interactive microprocessor control of positicn adjustments based upon sensing of visible light image by reticon diode arrays
Mirror Assembly Structures:	Mass production using numerically controlled machines to fabricate top, bottom, and side plates, .001" accuracy easily achieved
	Mass production of screw machine products relatively inexpensive in quantity
Imaging Proportional Counters	
Electronics:	No critical elements, extensive use of integrated circuits
Bodies:	Numerically controlled machines
	No critical tolerances
Wire Planes:	Special precision tooling facilitates wire winding
Reflection Gratings	
Surfaces:	Replication

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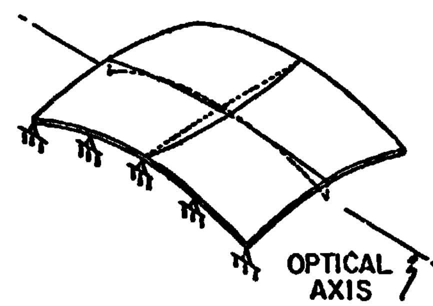
TABLE 4-2

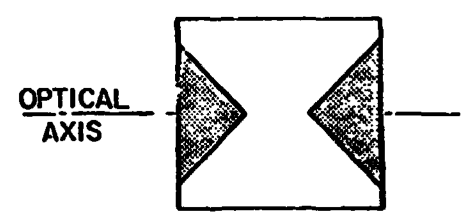
LAMAR MIRROR SYSTEM PERFORMANCE

(ENCIRCLED ENERGY vs. SYSTEM TYPE)

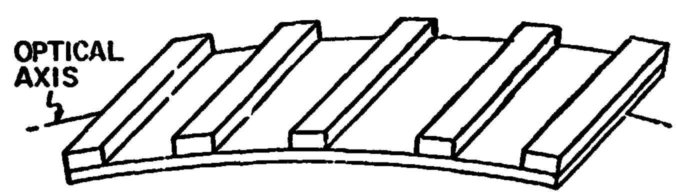
ADJUSTED BENT PLATE
(ON-AXIS OPTIMIZED)
50% ≈ 0.63 arc minutes diameter



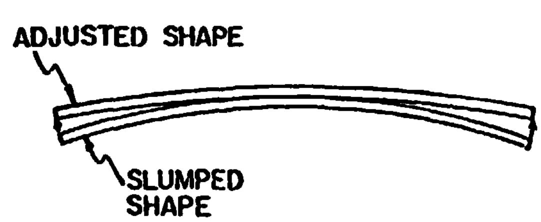
MASKED ADJUSTED BENT PLATE
(OPTIMIZED MASKED)
50% ≈ 0.59 arc minutes diameter
AREA LOST ≈ 18%



STIFFENED FLAT BENT PLATE
50% ≈ < 0.45 arc minutes diameter



ADJUSTED PRESLUMPED PLATE
50% ≈ 0.16 arc minutes diameter



PERFECT NESTED SYSTEM
50% ≈ 0.12 arc minutes diameter

NOTES:

- ALL NUMBERS APPROX.
- UNIT REFLECTANCE ASSUMED
- FOCAL LENGTH ≅ 213 cm
- 30.5 cm SQUARE PLATES ASSUMED
- NO INITIAL SURFACE RIPPLES ASSUMED

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Computer assistance would be useful for bending of the plates to the desired shape. Figure 6 illustrates the method that we plan to study. A microprocessor controls the position of a slit that can be driven along a precise linear encoder. A portion of a plate is illuminated by visible light through the slit. The line image is read at three points by diode arrays. The centroidal position of the three images are determined by the microprocessor. This information is used to drive stepper motors which apply bending moments to plate until the images are acceptable. The slit is moved to another part of the plate and the process is repeated. As experience is gained in this procedure the microprocessor program will be updated to incorporate refinements in the plate adjustment procedure.

4.2 Reflection Gratings

Although more definition of the reflection gratings is needed at the present time, it is expected that mass production methods are applicable. A nested array of identical grating plates would seem to be a good match to the optics of the nested plate telescope. Replication seems extremely promising as a method for producing a large number of identical gratings.

4.3 The Detectors

Imaging proportional counters (IPC's) in their various forms can be manufactured by well established and straightforward methods. The techniques include circuit board manufacturing, extensive use of integrated circuits as components, and numerically controlled machining. Little difficulty is

AUTOMATIC PLATE ADJUSTMENT

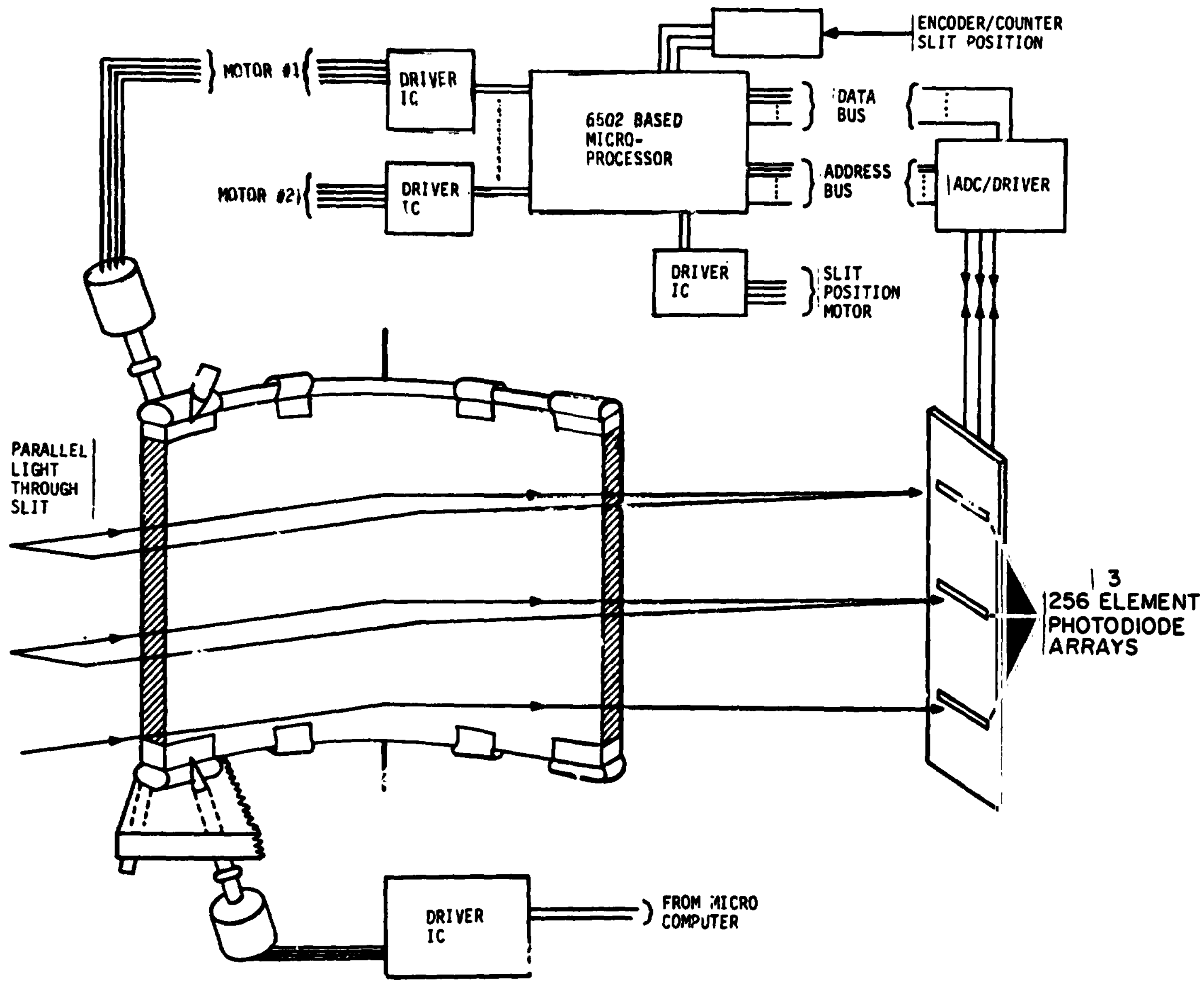

Figure 6

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anticipated in assigning these tasks to conventional manufacturing shops.

5.0 SUMMARY AND CONCLUSIONS

The high throughput capabilities of LAMAR will satisfy many of the requirements of future programs in X-ray astronomy. It will excell in measurements requiring:

- moderate resolution imaging for flux measurements and positions
- detection of low surface brightness features
- timing for temporal variability
- spectral measurements

The high throughput of LAMAR is unique and will greatly surpass that of all other telescope instruments, including the Einstein Observatory and all other facilities being planned for the future both in the U.S. and abroad. LAMAR is applicable to a wide range of scientific objectives and will serve many investigators.

The general utility of the LAMAR may be appreciated from an analysis of the guest observer usage by instrument of the Einstein Observatory. This is summarized in Table 5-1. Guest observer usage is a good indicator of how the astronomical community in general perceives the various instruments in terms of being relevant to their interests. The table shows that the Imaging Proportional Counter was the overwhelming choice both in terms of the number of observations and the total time in the focal plane. The essential characteristic of the IPC that

TABLE 5-1
EINSTEIN OBSERVATORY
GUEST OBSERVER STATISTICS BY INSTRUMENT

Total Time Done

IPC	-	6518.68 ksec	78.2%
HRI	-	1550.99	18.6%
SSS	-	229.10	2.7%
FPCS	-	39.60	.5%
TOTAL	-	8338.37 ksec	

Total Number of Observations

IPC	-	1571	90.7%
HRI	-	138	8.0%
SSS	-	20	1.2%
FPCS	-	2	.1%
TOTAL	-	1731	

resulted in its being selected so frequently was its high throughput. LAMAR will exceed the IPC of the Einstein Observatory by a factor of 50 in that capability which was found in practice to be most useful to the astronomical community as a whole.

Despite its large collecting area, the modular approach intrinsic to LAMAR will greatly simplify its development and will allow it to be compatible with a moderate cost Explorer mission.

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