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Foreword

For a number of years NASA Grant NSG-7643 has supported research at the MIT Center for Space Research aimed at the development of concepts and technologies for possible future space flight missions in high energy astronomy. This grant will expire as of 31 December 1990. This document is submitted in fulfillment of the contractual requirement for a Final Report.

INTRODUCTION

Since 1970 the X-Ray Astronomy Group of MIT has carried out the following investigations in X-ray astronomy based all or in part on concepts and instruments developed at the Center for Space Research:

Mission	Investigation
OSO 7	Multicolor Survey of Positions, Spectra, and Variations of X-ray Sources
SAS 3	X-Ray Observatory
HEAO 1	A-3 Scanning Modulation Counter Survey of X-ray Sources
	A-4 Survey of High Energy X-Ray Sources
HEAO 2	B-3 Focal Plane Crystal Spectrometer

Currently the MIT X-Ray Astronomy Group is developing instruments for the following missions planned for launch during the 1990's:

Astro-D	CCD Camera for the Japanese X-ray Telescope mission
XTE	All-Sky Survey
AXAF	CCD Camera for Imaging Spectroscopy
	High Resolution Spectroscopy (Transmission Grating Spectrometer and Bragg Crystal Spectrometer
HETE	High Energy Transient Experiment

NASA grants to MIT for investigations in experimental and theoretical high energy astrophysics have, over the years, nurtured the infrastructure development and experimental activities that have led to successful proposals for the above missions and to the achievements in high energy astrophysics of the MIT Group. In recent years these activities have been supported by Grant NSG-7643 for which this is the required Final Report.

This report consists of excerpts from the progress reports of 1988 through 1990 that have been submitted as a regular feature of the renewal requests. These excerpts convey the flavor of the grant-supported activities, and a sense of the progress that has been made in each of the areas investigation. For the sake of brevity all figures and references to them have been excised.

1988

<u>X-Ray Spectroscopy</u>

(Claude Canizares and Thomas Markert)

Our activities under this grant are directed toward the development and testing of techniques applicable to future astronomical X-ray spectroscopy instrumentation. Our main effort during the past year has been divided into two areas: (1) continuation of the upgrade of our 25m X-ray transmission grating test facility, especially the computer control of the grating motions and data collection, and (2) the reconstruction of a thin window leak test facility and the performance of leak tests on various window materials for possible use in proportional counters. We discuss each of these more fully below.

(1) <u>X-ray Transmission Grating Test Facility</u>

Our 25m facility consists of a high power X-ray generator, a grating test station with stepping motor controlled translation and rotation stages and linear encoder, and a slit-collimated, cooled Ge detector. The 25m X-ray beam travels through a He atmosphere in a lead lined ~2 ft diameter pipe. The He atmosphere facilitates the transmission of X-rays down to ~5 keV.

Over the past few years we have made a complete upgrade of this facility, including the purchase of a new American Instruments X-ray generator, a new Kevex Ge detector and the full stepping motor control hardware. Activities over the past year have included installation of the stepping motor assemblies, reshielding and full radiation safety survey of the facility, reconstruction of the X-ray head station, and the design and installation of a laser alignment system. This activity was funded in part by our AXAF phase B contract as well as by this grant.

One item highlighted in last year's proposal was the interconnection of the PM200 microcomputer instrument controller to the laboratory network of SUN and micro-Vax computers. This has facilitated transfer of data and software for instrument control and data analysis. Our original plan was to connect the PM200 directly to the CSR ETHERNET. However, we have decided to use instead a direct serial RS232 link between the PM200 and one of the micro-Vaxes, thereby eliminating the need to purchase a new controller board. The RS232 link did require installing the appropriate software to allow a user to log in remotely from the micro-Vax. That software has now been debugged. This will allow us, in the upcoming period, to improve significantly our data collection and analysis software.

As an example of the use of this facility, we have successfully tested an 0.2 μm period gold grating being developed for the AXAF High Energy Transmission Grating Spectrometer (from Fischbach et al. 1988).

(2) <u>Thin Window Test Facility</u>

In our last proposal we described our program of developing thin windows with ultra-low leak rates for use in proportional counters for soft X-ray detection. A major difficulty in the past has been obtaining reliable test data on windows at rates as low as 10^{-6} cc/cm^2-s. We had revived an old leak test assembly first used on the SAS-C project and later on HEAO-B (FPCS). However, the system did not give repeatable results at the lowest rates. The old apparatus had a system leak of 1.2×10^{-4} Torr/sec corresponding to ~0.2 cc/hr (measured using a blank in place of the window). This was only slightly smaller than the rates we want to measure, and was therefore unacceptable. For example, the measurements of a Formvar coated polypropylene window gave leak rates of 2.1×10^{-4} Torr/sec (0.13 cc/hr-cm^2) for Argon gas.

We carried out a series of tests of a polyimide window using Argon gas. The data are summarized in the following table:

Date	Corrected leak rate
8/2	0.0014 cc/hr-cm^2
8/6	0.037
8/10	0.079
8/12	0.10

The data show clear and steady degradation of the window material presumably due to the pressure cycling involved in the repeated tests. On the other hand, the initial leak rates are 100 times smaller than the HEAO-2 FPCS windows, and even the degraded polyimide windows are comparable to the polypropylene. With our new test apparatus we will try to understand the nature of the degradation to see if it can be prevented by proper mounting of the polyimide films.

As part of this year's effort, we have completely rebuilt the leak test apparatus. All the old TYGON tubing has been replace with copper and the system has been fully checked with a He leak tester. The new apparatus has a measured system leak rate of 3.4×10^{-6} torr/sec, 35 times smaller than the old one.

With this apparatus in place, we have recently renewed our leak test program. A first effort was to measure the properties of Formvar coated polypropylene windows similar to those flown on the HEAO-2 FPCS and baselined for the AXAF BCS. We have been carrying out a study of the failure modes that lead to high leak rates in these windows. This study has shown that most of the higher leak rate windows appear to have pin holes located under or at the edge of the strong-back on which the window is mounted. We want to test various methods of surface treatment to reduce or prevent the formation of these pinholes, and to see how aging and multiple repressurizations affect their appearance.

The first results are ambiguous. Of two windows tested, one showed a leak rate of 0.05 cc/hr (over the whole window area) and the other gave 0.19 cc/hr. We are now trying to determine the cause of this factor of four difference between the two values. However, the preliminary results are encouraging because the smaller value is about 1/3 the leak rate of our typical flight windows on HEAO-2.

X-Ray and Optical Image Analysis

(Claude Canizares and George Ricker)

During the past year, we have improved our image processing facilities in several areas. First, we added a low cost, 400 Megabyte hard disk drive to our Sun 3/160 workstation, which greatly enhanced the productive capability of this machine for image processing. The disk drive increases the total available disk storage space for image processing on other NFS-linked workstations to > 2 Gbyte. This now enables several users to store their optical or X-ray images on disk for ready access, allowing more than one or two people to be processing and analyzing images at the same time. The CSR Ethernet network lets computers share their hardware resources, including disk space and CPU. The two NFS-linked systems can therefore be used by anyone logged onto any machine in the building, accessing images or programs on the Sun or DEC/GPXs from other computers, or sending CPU-intensive computations to the computer which is being used least at the moment.

We have "ported" the latest versions of IRAF to both the Sun 3 and DEC/GPX computers. In addition, we are installing IRAF application programs (including FOCAS and 2DSPEC) as they become available, as well as X-ray specific programs which we have developed in our group at MIT.

We added several Macintosh computers for use as inexpensive black and white graphics terminals to allow users access to MicroVAX and SUN computers for image processing and other related computations. These added terminals have helped greatly in relieving the overload of people wanting to use the MicroVAX and Sun workstations.

Development and extensive use of the image analysis packages on both Sun 3 and VAX station II/GPX UNIX workstations acquired previously under this program took place during this past year. This effort included:

- Use of the FOCAS program for galaxy identification in optical images of X-ray galaxy cluster sources previously discovered by the Einstein Observatory [M. Bautz and students].
- Spectroscopic studies of X-ray selected rich clusters of galaxies with the YARP package [G. Ricker and students].
- Searches for faint Hα emitting filament systems in elliptical galaxies containing hot X-ray gas and cooling flows using YARP [P. Vedder and C. Canizares].
- Cataloging and daily evaluation of 'candidate reports' from a 6-month search with the ETC (May-September 1988) for optical flashes from the recurrent soft gamma-ray burster (SGR 1806-20; Atteia, *et al.* 1987)
- Utilizing the VISTA package for measuring low surface brightness features, including diffuse optical emission from X-ray clusters, down to limiting magnitudes fainter than B=+28 magnitudes/arcsec^2 [M. Bautz and students].

- Utilizing VISTA to search for correlated X-ray/optical variations present during simultaneous observations of the active galaxy NGC5506 with with EXOSAT satellite extending over four (4) days [R. Vanderspek and R. Ricker in collaboration with the Leicester X-ray Astronomy group].
- Utilization of FOCAS to distinguish X-ray induced events in CCDs from γ-ray induced events (G. Ricker and M. Bautz).
- Searching with YARP for optical counterparts with high proper motions to the well-localized, gamma-ray burst sources GRS 1410-78 and GRS 2251-02 down to a limiting magnitude of B = +26 [G. Ricker, E. Ajhar and R. Vanderspek].
- Searching with YARP for a time variable optical counterpart to the accurately-located (<1 arcmin-2) recurrent optical flash source (2 flashes in 1946, 1 in 1954) reported by Hudec (1986) down to limiting magnitudes of (B, V, R, I) < (+26, +25, +24.5, +23.5). [G. Ricker, E. Ajhar, J. Luu, and R. Vanderspek 1989, Ap. J. (Scheduled for March 15, 1989 issue.)]
- Improvement in the use of the FTP protocol, adapted from the National Center for Supercomputer applications TELNET package, to permit a 20-fold increase in file transfer rates, including laser printing, over a "bridged" Appletalk/Ethernet connection [E. Morgan].

The image analysis capability at the CSR built up over the past several years derives much of its power and flexibility from the extensive computer network now in place. The computer network consists of a local area Ethernet and an Appletalk/PhoneNet, connected by a Kinetics FastPath gateway. We also have direct gateways to the MIT campus network (and hence to Arpanet, Bitnet and NSFnet) and to the Space Physics Analysis Net. The following is a summary of the network.

ETHERNET HOSTS

File Servers:
- 1 × Sun 4/260
- 2 × Sun 3/260
- 1 × Sun 3/160
- 1 × Sun 2/170

Stand Alone:
- 3 × MicroVax GPX
- 1 × MicroVax II
- 5 × Pacific Microsystems

Diskless:
- 1 × Sun 3/110
- 6 × Sun 3/50
- 3 × Sun 3/60
- 4 × Sun 2/50

All ethernet hosts communicate via TCP/IP. The Suns and MicroVaxes run software that is compatible with version 4.2 of the Berkeley UNIX operating system. The Pacific Microsystems machines use AT&T versions of UNIX. All Suns and Micro Vaxes take advantage of the Network File System (NFS) to share their available magnetic disk storage (3.0 Gbytes).

Each Sun and MicroVax is equipped with a single high-resolution bit-mapped display. Three Sun displays and four MicroVax displays are in 8-bit color, the remainder are monochrome. In addition, the UNIX hosts have a combined total of 84 asynchronous RS232 ports available to support low-speed terminals, printers, and modems.

APPLETALK HOSTS
- 2 × Macintosh II
- 2 × Macintosh SE
- 5 × Macintosh Plus
- 11 × Macintosh 512

These hosts currently share two LaserWriter Plus printers. Two other LaserWriters are driven directly from Sun file servers. The FastPath gateway permits remote login and file transfer between the Macintosh and UNIX hosts at speeds of up to 300 Kbaud. We are currently testing software that will enable Macintosh hosts to share remote file systems maintained on UNIX hosts.

SHARED PERIPHERALS

In addition to the sharing of over 5 Gbytes of disk storage using NFS, discussed above, the Sun and MicroVax hosts share the following peripherals:

3 ×1600/6250 bpi tape drives
1 × 1600 bpi tape drive
1 × 2.6 Gbyte WORM drive
1 × Calcomp plotter
3 × LaserWriter Plus printers
1 Gateway to MITnet, Arpanet, and NSFnet.
1 × Gateway to SPANnet

SHARED SOFTWARE

All CSR network users have access to the following software:
- Compilers for Fortran-77, C, Pascal, and Magic-L
- SunWindows, SunView, and X-windows display managers
- Macsyma symbolic algebra interpreter
- IRAF, Gips, and Look image processing
- Mongo, Core, and CGI graphics
- TeX and Troff text processing

CCD Image Detectors

(George R. Ricker, John P. Doty, Gerry Luppino)

During the past year, we accomplished the following tasks in the area of CCD image detection Technology:

- Evaluated two generations of ultra-low noise MIT Lincoln Laboratory (MITLL) CCDs (420 × 420, 2 sided-abuttable device; 840 × 420, 3 sided-abuttable)
- Demonstrated the following characteristics of the MITLL CCDs:
  - low readout noise*: 1.6 e^- RMs
  - excellent low level charge-transfer efficiency*: > .9999997
  - low dark current: < 10^{-2} electrons pixel^{-1} s^{-1} at -70° C.
  *(These are the best values reported for any silicon X-ray sensor to date.)
- Measured the excellent spectral resolution (narrow FWHM) achievable with the MITLL CCDs at the characteristic lines of several "benchmark" elemental K lines:

Element	Energy	FWHM
Mn Kα	5.9 keV	117 eV
Mg Kα	1.25 keV	68 eV
O Kα	0.52	< 60 eV

- Evaluated the outstanding degree of linearity of the MITLL CCD over an extremely broad energy range in X-rays. The small origin offset of our measurements indicates that only ~ 2-3 electrons are being "lost" in the ~ 10^3 transfers of charge packets though the CCD.
- Confirmed that the theoretical dependence of energy resolution on X-ray energy is followed by the MITLL CCDs over a broad range.
- Successfully fabricated and tested a high resistivity MITLL CCD with excellent theoretical QE vs E. characteristics
- Demonstrated that there is an interesting energy resolution - quantum efficiency tradeoff in X-ray CCDs which can be very effectively exploited by software "adjustments". Thus, in future X-ray missions one can tune the instrument for high QE (e.g., continuum and timing measurements) or for the very best energy resolution (e. g., separation of the 6.4 keV and 6.7 keV Fe features).
- Wrote and utilized X-ray CCD energy response simulation tools to assist in evaluating the effects of incremental improvements in energy resolution on the deconvolution of complex spectral features in astrophysical plasma (e.g., the Fe L line complex).
- Demonstrated that excellent γ-ray rejection ratios are achievable with high-resistivity MITLL X-ray CCDs based on event topology screening. Rejection factors of 99.5 ± 0.3% have been achieved.
- Developed control and image analysis software tools for our Sun 3/160 CCD Data Acquisition computer to display and manipulate FITS format X-ray CCD images.
- For the High Energy Transient Experiment (HETE) project, we conceived a low-cost, near-real time direct data broadcast technique for making HETE burst positions (right ascension and

declinations) and intensity information available to ground-based observers within ~ minutes of the time of burst occurrence. Interest in participating in such a network has already been expressed by optical observers in a well-distributed network of observatories.

- Brought into service an Acton UV monochromator for testing CCD response in the 1800Å - 3500Å range important for HETE.

Cores of Galaxy Clusters

(John L. Tonry)

Clusters of galaxies are where the presence of a large component of mass in the form of dark matter was first suspected. They remain one of the best places to observe the gravitational effects of dark matter. Observations of the X-rays emitted by the hot gas found in many clusters have provided new measures of the gravitational potentials in the clusters since it can probably be safely assumed that the gas is in hydrostatic equilibrium with an isotropic distribution function. In most cases the spatial distribution of the X-ray emitting gas has a well defined core radius. In contrast, the distribution of galaxies generally does not (Beers and Tonry 1986) - the galaxies in the central parts have predominantly radial orbits (Tonry (1985A), and the distribution is often very clumpy. During the past year we continued our study of how these structural features and other observables such as richness, concentration, the presence of a cD galaxy, sub-clumping, and the presence of an X-ray cooling flow are related to the underlying skeleton of dark matter. The primary goal of this research is to trace the variation of M/L ratio with radius, from small values near the center of the cluster where the galaxies themselves dominate the potential, to large values where the dark matter dominates. (perhaps the core radius defined by X-ray observations marks the transition region.) Determination of M/L requires measurements of velocities for which we have a three-prong approach: (1) observe velocities of very close (~10 kpc) companions to brightest cluster galaxies in a complete sample of clusters, (2) observe velocities of moderately close (~100 kpc) companions in 6 clusters, and (3) observe velocity dispersions of the halo stars in several cD galaxies. Half of part (1) is complete and published (Tonry 1985B). Data for the other half of part (1), as well as all the data for part (2) are reduced and awaiting analysis. The observations for part (3) have been completed; the reduction and analysis remain to be done.

X-Ray Bright Elliptical Galaxies

(Claude R. Canizares, Atul Pradhan, John L. Tonry)

We have studied the possibility of combining X-ray data and optical velocity dispersions to constrain more precisely the properties of dark matter halos in elliptical galaxies. This effort has culminated in the Master's Thesis of A. Pradhan, "Constraining the Mass Profile of Spherical Galaxies Using X-Ray and Optical Data". We found that while optical and existing X-ray data can be used to complement one another, there are great improvements possible by extending optical observations to greater radii (very difficult) or by acquiring X-ray data with better sensitivity and spatial resolution (which will be provided by AXAF). Nevertheless, application of this method to the galaxy M87 revealed that the dark halo is dynamically important to radii as small as 10 kpc, indicating that it is associated with the galaxy and not just the Virgo cluster. It was also possible to show that unlike M31 and the Milky Way, that M87's globular cluster are heavily weighted towards circular orbits, most likely from the effects of dynamical friction.

Galaxy Distances from Surface Brightness Fluctuations

(John L. Tonry)

We have worked out a new method for determining the distances of elliptical galaxies based on the measurement of surface brightness fluctuations that arise from the counting statistics of the red giant stars in each pixel. The amplitude of these fluctuations is inversely proportional to the distance of the galaxy. The observed variance is also proportional to the apparent magnitude of a typical giant star in the stellar population, and is therefore promising as a probe of stellar populations.

Progress this past year has been comprised of a theoretical study of these fluctuations, determination of a reduction method to measure the fluctuations, implementation of software to carry out these reduction steps, and analysis of data gathered at the McGraw-Hill Observatory 1.3-m telescope. The results of this analysis shows that we can measure fluctuations in galaxies as distant as 20 Mpc, and give a preliminary distance for Virgo cluster of 17 Mpc. The method and early results have been reported in a recent article in the *Astronomical Journal*.

Quasiperiodic Oscillations

(Walter H. G. Lewin)

There have been several important developments in quasi-periodic oscillations (QPO) and "red noise" in the X-ray flux of bright low-mass X-ray binaries.

Hasinger (1987a,b) has proposed a phenomenological classification in which three different forms of QPO are coupled to the three X-ray spectral branches: the horizontal branch, the normal branch, and the flaring branch. This scheme seems to work well in many (not all) cases. In a recent review, Lewin, Van Paradijs and Van der Klis (1988) discuss this scheme, and its implications in detail. Hasinger (1988) suggests that the origin of the enigmatic spectral branches is connected to the regimes of sub-, Eddington- and super-Eddington accretion.

Following several reports of modest time lags (several msec) in the QPO and the red noise (see Lewin, Van Paradijs and Van der Klis 1988, and references therein), Mitsuda (1988a) found ~70-80 msec time lags (between high-energy and low-energy photons) in the ~6-Hz normal-branch QPO from Cyg X-2. This is uncomfortably high to be explained in terms of the recent Comptonization models (see e.g.: Hasinger 1987a; Wijers, Van Paradijs and Lewin 1987; Mitsuda 1988b), and some new ideas have been put forward (Mitsuda 1988b).

Recent results from Ginga observations (Lewin PI) have shown a correlation between the radio brightness and the X-ray spectral branches in GX 17+2. The data points with values for H_1 in excess of 0.04 relate exclusively to the horizontal branch data. The data points with H_1 values less than 0.04 relate to the normal and the flaring branch; the latter are indicated with a diamond. The two data points in the bottom panel (6 cm) with the lowest values for H_1 were obtained when the source was near the transition (apex) of the two branches. At 6 cm the flux densities appear somewhat higher on the normal branch than on the flaring branch, and they are by far the highest on the horizontal branch. The average 6-cm radio flux density (bottom panel) in the flaring branch was ~0.4 mJy; in the normal branch it varied between ~0.6 and1.6 mJy, and in the horizontal branch between ~4 and 7.5 mJy. At 20 cm (upper panel) the flux density is also by far the highest on the horizontal branch. We note that a similar result was found by Hasinger and co-workers (private communication) for Cyg X-2, and it is suspected that this connection may be common among the bright low-mass X-ray binaries (see Penninx et al. 1988a). In earlier models, Priedhorsky (1986) and Van der Klis et al. (1987) have attempted to explain the spectral branches, the QPO, and the radio emission for Sco X-1 by a theory of Comptonization of the photon flux. It now appears that these ideas, however useful they appeared at the time, may not work (Penninx et al. 1988b).

We found QPO in all three branches of GX 17+2. Of particular interest is the first and second harmonic in the horizontal-branch QPO, and the simultaneous occurrence of ~7-18 Hz and ~120-Hz QPO (Penninx et al. 1988b). The figure shows the power density spectrum of Ginga observations of GX 17+2. The vertical scale is logarithmic; the Poissonian noise has been subtracted. Two peaks are clearly visible. The one on the left has a centroid frequency of ~20 Hz. The ratio of the frequencies of the two peaks is 2.04±0.06; we have interpreted them as first and second harmonics. During these observations (in April 1988) the source was on the horizontal branch, and the centroid frequency in the first harmonic decreased from ~26 Hz to ~18 Hz; the frequency of the 2nd harmonic followed accordingly (Penninx et al. 1988b).

X-Ray Bursts

(Walter H. G. Lewin)

We have reevaluated many previously published results on type-1 X-ray bursts (data from SAS-3, Tenma, and EXOSAT) and found some very puzzling results (see, e.g., van Paradijs, Penninx and Lewin 1988). It appears that the energy in a burst is largely determined by the waiting time to that burst and does not depend on the mass accretion rate. This indicates that there is a constant "sink" of nuclear energy (the burning of He to higher Z elements) which increases as the accretion rate increases.

We also found, much to our regret, that the conversion from color temperature to effective temperature is a much more complicated function than what was previously believed (see e.g., London, Taam and Howard 1984,1986). It seems that the function is different for different sources (Damen et al. 1988; Penninx et al. 1988c). This has very unfortunate consequences for the possibility to evaluate accurately the mass and radii of neutron stars (Van Paradijs and Lewin 1988a,b).

In a systematic search through all type-1 EXOSAT bursts, we found a 4.1-keV absorption line during the rise of an X-ray burst from 1747-21 (Magnier et al. 1988). This energy is identical to that of the absorption features in bursts from 1636-53 (Waki et al. 1984), and 1608-52

(Nakamura et al. 1988); there is no doubt that they have similar origins. We have shown that the previous interpretation namely that this line is due to a gravitationally redshifted iron line could only be correct if the Fe abundance is at least ~400 times above cosmic abundance.

SAS 3 Data Archive Development: Eclipse Transitions of Her X-1 and Studies of the Black Hole Candidate A0620-00

(George Clark and Jonathan Woo)

One of the objectives of the separately funded effort on the extended analysis of SAS-3 data was the establishment of a data archive that could be accessed without recourse to the obsolete NOVA computers of the original project and the system-dependent analysis programs. The plan was to put the original processed data that resides on conventional magnetic tapes onto optical discs which can be accessed through the SUN-VAX network of the MIT Center for Space Research, and to modify the the essential analysis programs to run on the UNIX-based network system. To this end we procured an OSI WORM drive and transferred the SAS-3 Q-tape archive to a hard disc memory on the CSR UNIX-based network in preparation for transfer to optical discs. At this point we encountered a protracted delay due to the unavailability of a commercial or other software driver that would interface the OSI drive to the SUN system 3. We have made a number of false starts on this problem, and still have not found a satisfactory solution, though we are just now negotiating for a trial run with a commercial driver.

Meanwhile, following the termination of the extended SAS-3 data analysis project, we have been adapting the SAS-3 NOVA-based analysis programs to the UNIX based system of the CSR network, using a portion of the Grant funds to pay for the efforts of graduate and undergraduate research assistants. The effort has been motivated by the specific goal of analyzing in detail the eclipse transitions of Her X-1 and the variability of the great 1975 soft X-ray nova A0620-00. The latter object, whose optical counterpart was identified in 1975 on the basis of the SAS-3 position determination, is now the most firmly established stellar-mass black hole, thanks to the extensive optical research of McClintock and Remillard. Their discovery and measurement of the orbital period of the binary system, and their analysis of its optical phenomena have placed a conservative lower limit of 3 solar masses on the mass of the X-ray source, which virtually excludes the possibility that it is a neutron star, and points strongly to the conclusion that it is a black hole. Subsequent studies by others have confirmed this result. Thus great interest is now focussed on this nova and on all aspects of its observable phenomena. Extensive pointed-mode and scanning observations of A0620-00 were made by SAS 3 just after its discovery in 1975 and for many months thereafter till it faded from view.

We have undertaken a complete reanalysis of the archival data on A0620-00 in light of the new information about the orbital period. In particular, we are searching for orbital variations in the X-ray intensity that may reveal information about the accretion process of a black hole. A proposal was made during the past year to NASA's Data Analysis Program for support of this effort, and word of favorable action has recently been received. However, significant progress was made during the past year under Grant support. In particular, a senior thesis was completed on the topic of the value of or upper limit on the intensity of hard X-rays during the early period of the X-ray outburst. The results placed an upper limit on the >20 keV intensity that is substantially less than the value found somewhat later by the Ariel-5 observers. Thus it appears that the high-energy tail of the spectrum was "wagging" during the steady decline of the soft spectrum observed by both SAS-3 and Ariel 5. Similar variable hard X-rays have been reported in a recent soft X-ray nova discovered by GINGA in which the QPO phenomena has also been detected. QPO are generally thought to be a property of neutron stars. Thus an apparent and interesting contradiction may develop between the evidence that A0620-00 is a black hole, and the evidence that the similar soft X-ray nova of GINGA is a neutron star.

As for Her X-1, our work so far has extracted light curves of two eclipse transitions from the archive using the reworked analysis programs on the CSR UNIX-based network system, and we have established that the transition curves imply an atmospheric structure of HZ Her that is far more extended than is expected for an atmosphere of a 2 $M_{\odot}$ star with normal surface temperature, or for an atmosphere perturbed by X-ray heating, according to published models.

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1989

X-Ray Spectroscopy

X-Ray Grating Transmission Test Facility

In the past year we have continued to upgrade the automatic control of the test facility through both hardware and software improvements. The most significant change was the elimination of the the PM200 "middleman" in the system: the stepper motors and the pulse-height acquisition hardware are now interfaced to the μVAX, This allows control and analysis software to be integrated, gives access to a large memory space, and reduces the number of separate software systems, programs and languages.

The stepper motor interface was cleaned up through replacement of the COSMAC system with a commercial single board controller (Micromint BCC52) and associated stepper motor control card. This controller communicates directly with the μVAX via an RS232 cable.

The detection system interface was simplified through the replacement of our MCA (and associated interface hardware) with an IBM PC containing a single-board-MCA ("PCA"). Because of the power of the PCA system, dead-time corrected data are automatically acquired. The μVAX communicates with the PCA through an RS 232 link: down-loading collection instructions and receiving pulse-height spectra.

Our main effort has been in the development of software on the μVAX to perform automated (faster) testing sequences consisting of: moving gratings and slit, collecting PHA spectra, correcting these spectra for temporal variations in the amount of helium in the X-ray pipe through automatic interpolation of calibration files, extracting peak integrals, performing beam intensity normalizations, and arriving at a table of efficiencies as a function of angle or position. The subroutines that perform the data analysis are self documenting, i.e. each output file contains a history of the analysis steps that lead to it.

Thin Window Test Facility

During the first few months of 1989 we continued to evaluate thin polypropylene windows in our standard test facility. This apparatus consists of two chambers, one large chamber which is pressurized with a test gas and a smaller chamber which is evacuated with a mechanical pump. A pressure gauge is attached to the smaller chamber. The two chambers are separated by the membrane which is being tested. As gas leaks through the window the pressure rises in the evacuated chamber. Data taken when a polypropylene window, identical in design to the windows mounted on the proportional counters used on the Focal Plane Crystal Spectrometer (FPCS) experiment of the HEAO-2 (*Einstein*) satellite shows the rate of pressure increase is as small as any we have every seen in this sort of "standard" plastic window. This membrane (and several others fabricated at about the same time) was the culmination of a project to understand the source of pinhole leaks in proportional counter windows. By carefully investigating the source of leaks we were able to modify the technique of bonding windows to the detector strongback so that pinholes were essentially eliminated. The yield of "good" polypropylene windows (i.e., windows in which there are no pinholes and leaks occur through diffusion only) has risen, as a result of this project, from a few percent to well over 50%.

In addition to using the test apparatus to verify the quality of standard windows, we have also used it in other projects which have application to X-ray astronomy. For example, we attached a regulator to the high-pressure chamber which is capable of regulating the gas to pressures less than one atmosphere (we intend to operate the AXAF Bragg Crystal Spectrometer detectors at pressures ranging from 0.1 to 1.1 atmosphere). The goal of this experiment was to determine the leak rates as a function of pressure. This is important for the AXAF BCS (and other space projects which use gas flow proportional counters) so that we can accurately estimate the amount of gas required. We also measured the leak rate for various kinds of gasses independently so that we can predict the extent of differential leakage in a gas mixture.

In addition to using the test facility to evaluate and understand thin plastic windows, we have recently begun to use the equipment to study a new generation of thin films produced by the processes of chemical vapor deposition (CVD) and physical vapor deposition (PVD). These membranes are very thin and so are sensitive to very soft X-rays. Furthermore, it may be possible to fabricate them so that they are totally free of leaks (by this we mean that the time required for a leak to decrease the pressure in a proportional counter to such a degree that the performance of the detector deteriorates noticeably is greater than about 10 years). This is a very ambitious project, but it has a great potential benefit to all branches of X-ray technology. It is of particular importance to X-ray astronomy since it may allow the elimination of bulky and expensive gas replenishment systems in satellite-borne experiments.

In the past few months we have fabricated several thin (~1000 Å) windows consisting of Si_3N_4 (silicon nitride), supported by a grid of silicon. We modified our window holder so that it could accept such films, and then performed the standard tests. The silicon nitride is ten times thinner than the polypropylene, but it leaks at a rate at least 30 times less. Furthermore, the nitride leak rate is only slightly greater (about a factor of 3) more than the system leak rate as measured by installing a thick silicon wafer in place of the test film.

Even a small leak, however, is unacceptable if we wish to make a long-lived sealed detector. Therefore we would like to locate the source of the residual leak, and take steps to remove it. We have recently ordered (in partnership with the CCD group) a sensitive helium leak detector with a precise sniffer probe (accurate to about 1 mm). We plan to fill the high-pressure chamber with helium and remove the low pressure chamber entirely (i.e., expose the test piece to the lab environment) and measure the leak rate of helium through the membrane. Pin-hole leaks should be easily located with the sniffer probe. Leaks through the O-rings and/or through the epoxy bond should also be found quickly. Because the helium leak detector is so sensitive, furthermore, leak measurements should be performed much more rapidly.

6.1.1.3 Background Reduction in Imaging Proportional Counters

The equipment required for the analysis of background produced by cosmic rays and other radiation environments in imaging proportional counters has been acquired. We have also procured a 1"x4"x5" crystal of bismuth germanate (BGO) which we will test as a high-Z and high-density active shield against gamma-ray induced background. We are currently in the process of assembling the equipment and modifying the existing measurement chain of the imaging counter in the HEAO-B vacuum facility so that coincidence and anti-coincidence logic can be applied to the analysis of complex background-inducing events.

6.1.2 X-Ray and Optical Image Analysis

During the past 12 months, we were successful in introducing both the IRAF Ver. 2.7 (Tody et. al. 1987), VISTA, and the DOPHOT image processing packages to the SUN 3 and μVAX/GPX workstations. These three packages are useful for both optical and X-ray CCD image analysis. For CCD X-ray data acquisition, a new suite of programs, called CCCP, was developed by J. Doty or our group. Extensive use of the Macintosh II-based platforms acquired under this grant in the past year, using a direct Ethernet link to the CSR Local Area Network (LAN) in accessing and editing image files through the NCSA Telnet 2.3 protocol, has been successful. During the remainder of this year, we plan to test a version of X-Windows for the Macintosh II, which will permit full use of the Macintosh II as a low-cost image processing platform on our LAN.

6.1.3 CCD X-Ray and UV Image Detectors

During this past year, we either fully accomplished the study goals we set out in 1988, or identified alternate approaches which have proven to be more productive. As outlined in our 1988 proposal, these goals were that:

"...During the coming year we plan to emphasize CCD studies in five areas:

a) Development of ultra high-resistivity ($\rho > 2000\ \Omega$ cm) CCDs for '2nd generation' X-ray detectors.
b) Computer modeling and laboratory testing to establish the limits to non-X-ray background levels in CCDs.
c) Development of long-lead items for the High Energy Transient Experiment (HETE) mission.
d) Refurbishment of our laboratory CCD X-ray system to permit absolute QE measurements at low (<1 keV) X-ray energies.
e) Upgrade of our portable CCD X-ray camera to facilitate its use at locations away from MIT (e.g., synchrotron light sources)...."

a) Development of Ultra High Resistivity X-ray CCDs

In activity a) we demonstrated 1500 Ω-cm high-resistivity X-ray CCD detectors. The performance of these devices in terms of low dark current, good charge transfer efficiency, and energy resolution was as good or better than the low resistivity ($\rho > 100\ \Omega$ cm) CCDs developed prior to 1989. The actual measured quantum efficiency of these devices is 64% at 5.9 keV, in satisfactory agreement with the value of ~70% we calculated they might have in 1988. Furthermore, we currently have both 3000 Ω cm bulk and 2000 Ω cm epitaxial CCDs in fabrication for our use at MIT Lincoln Laboratory. If successful, the 3000 Ω cm devices will permit depletion depths in excess of 80 μm, which should result in quantum efficiencies of ~90% at 5.9 keV.

b) Modeling and Laboratory Testing to Establish Non X-ray Background Limits for X-ray CCDs

During the past year, we undertook an extensive study of charge transport in high-resistivity CCDs. This work involved developing a detailed model for charge motion in 1000 Ω cm devices. These models permitted a comparison of simulated charge flow in actual CCD structures with such observables as pixel "event-splitting" and histogram profiles. We have calculated the electric field potential contours for our model for the MIT Lincoln Laboratory 420x420 CCD array, for a bias gate setting of OV. The closed contour within 7.5 V shows the "buried channel" within which charge is collected. We measured the distribution of the charge packet at an elapsed time of 100 psec after the packet is produced by an X-ray interaction at a depth of 9.6 μm from the top surface of the CCD. This is a "single movie frame" from our simulation, which shows the detailed evolution of the charge cloud. Because of computer limitations, we were only able to carry out 2D simulations in 1989. (During the coming year, we plan to use MIT's Cray 2 to simulate the full 3D development of charge packet spreading within the CCD.).

c) System Development for the HETE Mission

During 1989, the UV response of a thinned, backside-illuminated MIT 420x420 CCD was demonstrated. The quantum efficiency (QE) at 3500Å is 14% without anti-reflection (A-R) coating. With the addition of a suitable A-R coating, we expect to increase this QE to a value near 25%. (For HETE, we have assumed that detector QE values in the range 15% - 30% will be achievable.) We are continuing to test the stability of the UV response of our MIT CCDs. If they are indeed stable, as we expect they will be, then it will not be necessary to investigate lumigen-coated CCDs, and a much simpler HETE detector assembly and test procedure will result. Also during 1989, we carried out a study of a Digital Signal Processor (DSP) - based CCD data handling scheme for HETE. The proposed DSP-based signal chain for HETE results in a 30-fold reduction in power required for on-board data acquisition and reduction for HETE, compared to previous non-DSP designs.

d) Refurbishment of CCD Laboratory X-Ray Generation System for Low-Energy Absolute Quantum Efficiency Measurements

In our refurbishment of the MIT CCD Laboratory X-ray generation system, we were able to design a crystal monochromator using multi-layer diffractors, similar to the scheme of Craig et.al. 1988 (S.P.I.E. **982**, p. 362). This monochromator is being fabricated presently, and should be in operation by January 1990. In related work, we began measuring the relative response of an MIT 420x420 CCD using an absolutely calibrated Fe-55 source. We find that the device has a non-uniformity of ± 1.8 % (1 sigma) at 5.9 keV. Similar studies are planned at $E_x < 1$ keV using our new X-ray monochromator as soon as it is completed.

e) Upgrade of Portable CCD X-Ray Camera System

The "upgraded" portable CCD X-ray system constructed under this grant was used to carry out measurements of proton-induced radiation damage in CCDs at the 160 MeV Cambridge Cyclotron. Our camera has been placed in the beam line at the Cambridge Cyclotron. We measured the effect of 600 rads (Si) of exposure on the charge transfer efficiency (CTE) of one of our *unshielded* low-resistivity devices. The degradation effect is quite significant, and requires study in the coming year, as well as efforts to further "harden" the CCD structure, as well as to plan proper shielding for satellite missions.

Optical Studies of X-Ray Sources

(John L. Tonry)

Cores of Galaxy Clusters

Data pertaining to the proposed study of the cores of galaxy clusters has been obtained and reduced. Analysis and interpretation are underway.

Galaxy Distances from Surface Brightness Fluctuations

A central problem in extragalactic astronomy is the measurement of distances and the determination of the value of the fundamental extragalactic distance parameter., the Hubble constant. For two decades in all areas of extragalactic astronomy quantitative results involving the Hubble constant have been quoted with an explicit "fudge" factor allowing for a possible change in the Hubble constant by as much as a factor of 2. This factor represents the present disagreement between two major schools of thought on the subject of the cosmic distance scale.

We have recently developed a new technique for measuring distances that we believe will be useful well beyond the Virgo cluster, and we have published papers on the method and on the first results from observations of Virgo from Kitt Peak National Observatory. This method leapfrogs a number of steps in the traditional cosmic distance ladder in which, many of the present uncertainties reside. We anticipate that its development will benefit extragalactic astronomy in general and high energy astronomy in particular by narrowing the uncertainty in the distance scale, and as a consequence reducing the uncertainty in our knowledge of the physical conditions and evolutionary processes that give rise to X-ray emission from galactic nuclei, halos, and clusters of galaxies.

As a byproduct of this research, we have developed techniques for discerning details in elliptical galaxies that may help elucidate the apparent "lumpiness" of the X-ray profiles of elliptical galaxy halos. We also expect to be able to understand better the nature of stellar populations in elliptical galaxies from which the X-ray-emitting gas is derived.

The new technique involves measuring in early-type galaxies the "surface brightness fluctuations" which are pixel-to-pixel fluctuations caused by Poisson fluctuations in the number of bright stars encompassed by each pixel. The amplitude of the fluctuations gives the flux from a *single* red giant star, and can provide the galaxy's distance if the star's luminosity is known, or can determine the star's luminosity if the distance is known. The method is therefore of interest both for determining extragalactic distances and for the study of stellar populations. We have published details of the method (Tonry and Schneider 1988), and some of the first results obtained from observations with the MDM (Michigan-Dartmouth-MIT) 2.4 m telescope (Tonry, Luppino, and Schneider 1988).

The second step in the development of the method has been to observe a number of galaxies at the same distance in order to separate the effects of distance from stellar population variations. The Virgo cluster is ideal for this purpose, and we observed 13 Virgo elliptical galaxies on the KPNO 4-meter telescope in very good seeing conditions. The data are mostly reduced and the first results are in press (Tonry, Ajhar, and Luppino 1989). We find that the distance to the Virgo cluster is 14 Mpc, which translates into a Hubble constant of 88 km/s/Mpc. We were delighted to find that the actual measurement of the fluctuations is quite easy given good data, and we believe that we can extend the technique to galaxies at a distance of 40 Mpc. We expect to perform a more sophisticated analysis of all of the data which should solidify our understanding of how the stellar populations vary from galaxy to galaxy.

Interpretation of X-Ray Data

Bursts and Quasi-periodic Oscillations

(Walter H. G. Lewin)

In our continuing search for quasi-periodic oscillations in the intensity of low-mass X-ray binaries we have discovered unusual oscillations in the *persistent* emission of the Rapid Burster after several type II bursts; the period (~25 sec) decreases as the oscillations die out. These oscillations are somewhat reminiscent of the oscillations often observed during burst decay (Lewin et al. 1976; Kawai 1985; Tawara et al. 1985; Tan et al. 1989). All three bursts reach a peak counting rate of ~1100 counts/sec (off scale). A brief burst-like event (or oscillation?) immediately after the third burst occurs during the "dip" in the persistent emission.

We have also discovered two bursts (of type II?) from the Rapid Burster which are triangular in shape and which show very strong oscillations with a period of ~0.7 sec; the modulation is nearly ~100%. The frequency of these oscillations is very similar to the QPO observed in type II bursts (Stella et al. 1988), and we suspect that the two are related.

Three type II bursts from the Rapid Burster each followed by distinct oscillations in the persistent emission were recently discovered by us. The ~25 sec period of the oscillations decreases as the oscillations die out.

We have examined bursts from 1636-53 and found there is a strong correlation between the burst duration and the spectral state (location in the color-color diagram); there is also a strong correlation between the spectral state and the blackbody temperature observed during the burst at the moment that the burst flux has decayed to 10% of the Eddington flux ($T_{0.1}$). The correlation is striking; long bursts with durations ~20 sec which have relatively high values for $T_{0.1}$ ($kT_{0.1}$~1.3 keV) exclusively occur in one part of the color-color diagram, and short bursts (~5-10 sec) which have relatively low values for $T_{0.1}$ ($kT_{0.1}$~1.1-1.25 keV) exclusively occur in another part.

Analysis of SAS-3 Data on the Eclipse Transitions of Her X-1 and Analysis of A0620-00

(George Clark)

Our analysis of the SAS-3 data on the eclipse transitions of Her X-1 has yielded values of 2.7×10^9 cm for the effective scale height of the HZ Her atmosphere. The temperature of a hydrostatic isothermal atmosphere in the same gravity would be 9.7×10^4 K, which is much higher than the observed surface temperature of HZ Her. These results are in qualitative agreement with results obtained from the much more extensive data obtained from EXOSAT.

For the analysis of the A0620-00 data a new application program was developed for fitting the detector response to the scanning-mode data. This research is now supported by a separate data analysis grant.

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X-RAY SPECTROSCOPY
LEAK-TIGHT THIN WINDOWS FOR SOFT X-RAY DETECTORS

(Thomas Markert and Claude Canizares)

The Bragg Crystal Spectrometer (BCS), currently under development for possible use in the AXAF, employs two redundant position-sensitive proportional counters with formvar-coated stretched polypropylene windows that permit operation down to energies in the soft X-ray range from 0.14 to 0.28 keV where spectral information of special importance to the analysis of the composition and physical state of nebular X-ray sources is to be found. Similar windows were used in the soft X-ray counters of the SAS 3 and *Einstein* missions and lasted in both cases for the durations of the missions. Thus there is good reason for confidence in the baseline BCS design. However, such windows do leak, and the required gas replenishment system is heavy, complex and expensive. Clearly it would be desirable to develop and use leak-tight windows that eliminate the need for a gas replenishment system entirely. Failing that, it would be useful to develop windows with significantly smaller leak rates so that a smaller gas system would suffice for the long AXAF (up to 15 year) mission. Motivated by these considerations, we have for several years been working on the technology of ultra-thin membranes.

While the BCS application was our initial motivation for thin window development, any X-ray instrument in which it is necessary to confine gases and transmit X-rays will benefit from the use of membranes which are both thin and leak-tight will be important. In particular, a proportional counter which must operate below 1 keV and any X-ray detector that would be contaminated by atmospheric gases would benefit from such windows.

Since beginning our development effort we have discovered two parallel research projects being carried out in Europe. The European Space Agency has a contract with Outokumpu, Inc. in Finland to produce a set of such membranes for their proportional counter research. The Danish Space Research Institute also has a contract with Outokumpu to produce large (140 mm diameter) windows for their proportional counter detectors for Spectrum-X-Gamma.

At MIT we have recently formed an ad hoc "Membrane Group" consisting of representatives from several research projects. These include the AXAF BCS group, the ASTRO-D CCD group, representatives from the Submicron Structures Lab (SSL, the laboratory which is fabricating the High Energy Transmission Gratings for AXAF) and a group from the Center for Astrophysics who are developing detectors for the X-ray Calibration Facility at the Marshall Space Flight Center. While each of the representative organizations has its own goals, we have enough common interests to make a such an umbrella organization worthwhile. We share information and divide tasks according to our special interests and abilities. While our ultimate goal has not yet been attained, we have made significant progress and have demonstrated 2 types of low-leak membranes and procured a sample zero-leak membrane.

Current Status

X-ray Transmission Requirements

Over the past two years we have investigated the following candidate materials for X-ray transmission and gas-leakage properties: silicon nitride (Si_3N_4), polyimide, diamond, and beryllium. We have considered only those materials and membrane thicknesses that gave a significant X-ray transmission ($\geq 10\%$) at 500 eV (consistent with the requirements for current MIT applications).

Leak Rate Results

All of the new candidate materials are reputed to have leak rates significantly less than that of stretched polypropylene. We have measured the rates of some samples of polyimide and Si_3N_4 (the two materials fabricated at MIT), in a leak detecting device originally constructed for evaluating polypropylene windows. This apparatus consists of two chambers separated by a test window. One chamber is pressurized to one atmosphere and the other is evacuated and then sealed off. The pressure in the evacuated chamber is monitored as a function of time. Because the leak rates in the candidate membranes are so low, we also measure the leak of the system as a whole by replacing the test window with a thick silicon blank through which there is no gas diffusion.

These tests showed that both the polyimide and Si_3N_4 windows leak at a rate approximately a factor of 30 less than the polypropylene.

This leak apparatus was designed for evaluating plastic membranes which were known to leak copiously. The new generation of membranes leaks at a much lower rate and, in fact, the system leak rate (through various seals and O-rings) is comparable to the membrane rate. Furthermore, because leak rates are so slow, tests can require a day or so before the manometer can measure a significant increase in pressure.

In order to evaluate improved windows, therefore, we have acquired and are now using a Balzers HLT 150 helium leak detector. We have designed and built a window holder and test chamber in which the system leaks are very small and are continuing to work to make the apparatus tighter. The Balzers detector is considerably more sensitive than the equipment previously used, so tests can be performed much more rapidly. Early results with a 0.75 inch diameter silicon nitride membrane (~1.5 μm thick) are extremely encouraging, indicating a leak of less than 10^{-9} $cm^3/sec/cm^2$ at one atmosphere. If this rate can be repeated for a thinner membrane, it will meet our requirements for a sealed proportional counter.

Window Support Systems

Only very small X-ray windows can support a significant pressure without additional structure. For example, KeVex manufactures an unsupported window (probably boron nitride) which has excellent X-ray transmission and leak properties, but is only available in 10 mm^2 samples. For most applications, which require windows with areas of at least several cm^2, the X-ray membranes have to be supported with mesh, a fine grid, a coarse grid, a strongback, or some combination of these. For the candidate materials discussed above, an additional constraint is that some of the membranes can only be fabricated in small sizes. Consequently, if they are to be utilized they must be attached to a strongback as individual window panes. Finally, the method used to attach windows to their frames is an issue. Since the materials can be quite delicate, the bonding must be performed with great care.

The baseline design for the BCS detector had a very large window (6.0 x 2.5 inches) supported by an aluminum strongback and a tungsten mesh. We have redesigned the strongback so that the support geometry consists of smaller rectangles and so that the aluminum ribs are wider, wide enough to accommodate the sides of window "panes" which can now be bonded individually to the ribs. This redesign frees us to use 15 smaller window sections, rather than a single large piece of stretched polypropylene.

Tungsten mesh (which is a woven "fabric") is probably too rough for the candidate materials. Even commercially available electroplated meshes can develop kinks and cause problems. We have considered two techniques for fabricating a supporting gridwork which is in direct contact with the membrane (and hence adheres to it smoothly): one technique is to pattern a mesh into the silicon wafer which remains in place when we etch away the wafer and expose the membrane; a second technique is to electroplate a metallic mesh (nickel typically) directly onto the membrane. We have been developing both methods at MIT. The first (patterning a fine grid into the silicon wafer) works well on small spatial scales, but for larger samples the silicon grid itself seems to rupture at one atmosphere differential pressure. Electroplating appears to be the most promising method at this time and the one on which we are expending most of our efforts.

Different applications will, of course, place different requirements on the support structures. We are striving to make the sizes of the unsupported areas as large as possible, and to be as versatile as possible with our strongback and mesh designs, so as to accommodate future applications.

Progress with the Four Candidate Materials

Polyimide - Polyimide is prepared by spinning a solution of the material onto a silicon wafer in the Submicron Structures Lab "spinner". The central part of the wafer is then etched away in a chemical bath leaving the thin membrane supported on its outer rim by the unetched wafer (as noted above, a grid can be patterned into the wafer to provide additional support when the membrane is pressurized). Typically we work with 2 or 3 inch diameter samples, but much larger diameters (up to 6 inches) are possible. A new formula polyimide (2610D) developed by DuPont shows promise as a leak-tight membrane which appears to be much stronger, much less susceptible to water and humidity damage, and seems to leak at a significantly slower rate than older polyimide formulations.

The 2610D material leaks at a rate approximately a factor of 30 less than the polypropylene. Our colleagues at the Center for Astrophysics have pressurized a small sample, obtained from our labs, to a differential pressure of 54 psi before the membrane broke (this was a 5 mm diameter sample of 1 μm thick material, totally unsupported). A sample of the old polyimide (DuPont 2555) burst at $\Delta p = 9$ psi. The 2555 was clearly affected by humidity (it would wrinkle noticeably on a humid day); 2610D shows no such effects. All in all, DuPont 2610D is a very promising material.

So far we have experimented with small samples of polyimide, unsupported and uncoated with any other materials. At the same time as we have been working with this material in our lab, we have also been in communication with Outokumpu, Inc., the Finnish company which is fabricating low-leak polyimide windows for the Danish Space Research Institute and for the European Space Agency. Outokumpu has produced low-leak membranes, 20 mm in diameter, made of polyimide (1.5 μm to 2.5 μm thick) coated with 600 Å of aluminum. These membranes are supported with a fine tungsten mesh and a coarser tungsten grid. While Outokumpu has, thus far, demonstrated a rather low yield of successful windows, they have produced some with very low leak rates (their best has a helium leak rate of 1.5×10^{-9} $cm^3/s/cm^2$ at one atmosphere). These rates are very good, and we will certainly consider their technique of aluminum coating (which they claim retards gas diffusion) on our 2610D membranes.

Silicon Nitride - We have done a great deal of work with silicon nitride at MIT, primarily because it is an essential component in the X-ray masks used in the X-ray lithography process required for the High Energy Transmission Gratings on AXAF. Our leak tests with this material are very promising and the X-ray transmission, particularly for the thinner membranes, is extraordinary.

Over the past year we have been working in a number of areas to improve our silicon nitride so it can be a viable candidate for the various X-ray astronomy applications:

Supporting large membranes: General support techniques were discussed above. Fairly large samples (diameter ~ 0.75 inches) of silicon nitride can be supported by rubber O-rings. The flexibility and curvature of the O-ring allow the nitride to bend gently (a sharp-bend, for example at the wafer-membrane interface, invariably leads to fracture when the nitride is pressurized). We are currently working on methods of supporting larger samples of Si_3N_4, perhaps using an electroplated grid in conjunction with an O-ring or ordinary strongback. One possible drawback to using an O-ring (which may be overcome in the mechanical design) is the leakage of gas around the O-ring seal.

Evaluating the material properties of the membranes: The nitride material is deposited onto the silicon wafer by a chemical vapor deposition process in which low pressure gases at high temperatures stream past the wafers. At the present time this process is more art than science, and the material tends to be deposited differently (in terms of its internal stress, elasticity, elastic limit, thickness, and exact composition) from run to run and from wafer to wafer within a wafer boat (each boat holds 25 wafers). We have been trying to measure these properties whenever possible since they can help us to understand the physics of the membranes and to predict which membranes are likely to survive pressurization. Clearly the composition and thickness of the membranes must be known if we are to be able to predict the X-ray transmission. A long-range goal is to be able to control the parameters better so we can obtain a high yield of acceptable membranes.

We have developed a number of tests (and are working on more) to help us evaluate the membrane parameters. While these have been applied most extensively to silicon nitride films, we also use many of them in our studies of polyimide membranes. These are:

Deflection testing: Membranes are subjected to gradually increasing pressures and the deflection of the film is measured with a microscope. Plots of deflection versus pressure allow us to compute the internal stress, the coefficient of elasticity, and the elastic limit of the material. Some membranes are pressurized until they rupture, thus giving us the burst strength of the material (obviously this is a destructive test).

Acoustical resonance testing: A tunable loud speaker and microphone are used to find the resonant frequency of the membrane. The resonant frequency can be used to compute the internal stress of the membrane.

Membrane thickness: One technique for measuring the thickness is to take a small sample of membrane material and run a stylus profilometer over it. This is hard to do accurately since the membrane doesn't always lie flat. We are now working on an optical technique to make the same measurement.

X-ray transmission tests: This technique measures the product of the membrane thickness and its density and also gives some information on the chemical formula. The actual formula for silicon nitride is not well known. It is ostensibly Si_3N_4, but in fact it is more appropriate to refer to it as Si_xN_y, where $x \sim 3$ and $y \sim 4$. The formula is uncertain because the nitride deposited in the CVD process is not stoichiometric, but is silicon enriched (enriched nitride is preferred because it has a lower internal stress and is stronger). Unfortunately, the actual formula of our nitride is hard to determine from the X-ray transmission method because the X-ray opacity is not too sensitive to the amount of nitrogen present. We are working on alternative techniques for determining the formula (see below).

X-ray Photoelectron Spectroscopy : A promising technique for determining the chemical formula of a material is to bombard the material with X-rays of a fixed energy and then measure the energies of the photoelectrons emitted from the surface. This method, called X-ray Photoelectron Spectroscopy (XPS) is available as a purchased service from the MIT Materials Science Department. We have not been too successful with XPS thus far, because it seems to be subject to contamination (it measures the surface composition only, so the surface must be quite clean). We are also investigating alternative methods such as pyroanalysis, Rutherford scattering, and ESCA (electron spectroscopy chemical analysis).

Diamond - We have had several discussions with technical and sales people at Crystallume, Inc. (Menlo Park, CA). Crystallume is the only commercial vendor of diamond membranes that we are aware of, and they actually sell a small (6 mm diameter) leak-free film.. They have supplied us with a sample window which we intend to use in an acoustic test (see below). In addition, they are anxious to respond to the BCS (and other applications). In spite of the fact that their presently available commercial window is too small (probably) for our satellite applications, they seem confident that a larger window (perhaps with some additional support structure) can be made. In the near future we will send them the BCS requirements (including options on strongback, X-ray transmission, etc.).

Beryllium - We have obtained a 5 μm thick, 60 mm diameter beryllium foil (produced by a patented vacuum evaporation technique) from Yamaha, Inc, for testing and evaluation. Yamaha has performed some work with 10 μm thick material, and have developed a technique for supporting it against one atmosphere pressure. We have not yet attempted to test this foil in our own facility for several reasons: (a) the 5 μm sample is too thick for most applications, (b) beryllium is quite difficult to work with, (c) the support technique suggested by Yamaha is rather complex, and (d) we have seen no measurement of the leak rate of even the relatively thick (10 μm) Yamaha membrane.

In view of the difficulties of working with beryllium and the various uncertainties concerning such a foil, we have given it the lowest priority of the four candidate membrane materials.

BACKGROUND REDUCTION IN IMAGING PROPORTIONAL COUNTERS

(George Clark and Thomas Markert)

The Bragg reflection spectrometer employed in the FPCS experiment on the *Einstein* observatory and the Bragg Crystal Spectrometer proposed for the AXAF mission employ position-sensitive proportional counters with thin windows and wire-wall anticoincidence shielding to detect the focused beam of X rays reflected from the curved crystal diffractor. Most of the background counts that pass the anticoincidence requirement are rejected by application of the following criteria: 1) the pulse shape must fall within limits characteristic of the very localized ionization caused by the electrons ejected in photoelectric interactions of low-energy X-rays; 2) the pulse amplitude must fall between limits corresponding to the expected energy of Bragg-reflected X- rays; and 3) the position of the count must fall within the focused image of the aperture slit. In the case of the FPCS the rate of background counts that passed these criteria was approximately 1.5×10^{-2} s^{-1} in a typical observation of a spectrum line near 1 keV. It is this rate that set the ultimate sensitivity of the high-resolution spectrometry on the *Einstein* mission. A similar background rejection scheme is employed in the BCS instrument, so one can anticipate a similar background rate, scaled up, perhaps, by the ratio of the fiducial volumes of the counters. The minimum observing time required to achieve a specified signal/noise ratio diminishes in proportion to the square root of the background rate. Thus any gain in background reduction technology will pay dividends in increased observing efficiency and/or increased sensitivity of future Bragg spectrometers.

Two years ago we began a small computer-modelling study with an undergraduate research student (J. Mohr) to explore the possible significance of secondary radiation from the walls of the proportional counter in generating background pulses. In CY90 he expanded the effort as a senior thesis with experiments on the use of active shielding by bismuth germanate to attenuate the background-producing effects of ~Mev gamma rays, and a more ambitious effort to develop a Monte Carlo model of interactions of the gamma rays in the counter walls with production of background-causing secondary photons.

Background events not suppressed by the current selection criteria of the BCS include:

a) interactions in the fiducial volume of bremsstrahlung X-ray photons generated by energetic electrons in the walls of the counter.

b) Compton scatterings of energetic photons that yield recoil electrons in the accepted energy range of the pulse-size discriminator.

c) neutron-induced events.

During 1989/90 we acquired the pulse electronic test equipment specified in CY89 proposal and set up the necessary apparatus to explore background suppression by active shielding with a bismuth germanate (BGO) scintillator. Tests of the efficacy of BGO as a shield against ^{60}Co gamma rays were made with the IPC and associated data system of the BCS development laboratory. In addition, progress was made in development of the Monte Carlo code for tracking electromagnetic radiation through shielding material, the walls of the IPC, and into the fiducial volume.

Current Status

As described in Mohr's thesis, a set of subroutines was coded which treat the dominant electromagnetic interactions in the 0.1KeV-1.33 MeV region. A source of specified characteristics emits ~MeV photons into a region of solid angle which can include a detector. The Monte Carlo code tracks the incident photon and its secondary photons and electrons through the material of the detector and whatever shielding may be interposed. For each event the amount of energy lost by ionizing collisions of the secondary electrons in each of several designated regions of the shield and detector is recorded. Various selection criteria, corresponding to realistic electronic selection schemes, can then be applied to the Monte Carlo results to obtain predicted background reduction effects that can be compared with the measurements made with the BGO shield. The subroutines for computation of the Compton scattering, photoelectric absorption, bremsstrahlung, and ionization loss have been coded and debugged.

On the experimental side, progress was made in understanding the nature of "background" events in the IPC caused by exposure to ^{60}Co gamma rays from the back side. It was shown the the differences in energy spectra of pulses from the various wires of the wire-wall detector are consistent with the expectation that the induced background is due to secondary low-energy photons generated in the aluminum walls of the IPC.

The 4"x5"x1" BGO crystal, connected to two RCA 6342A photomultipliers by light pipes optically coupled to the 4"x1" faces of the crystal, was calibrated with cosmic ray muons selected by a coincidence telescope. Interposing BGO crystal between source and IPC shielding reduced the ^{60}Co background by the expected attenuation factor for 1.1-1.3 MeV gamma rays. No additional reduction was obtained with the BGO shielding in active mode operation.

CCD X-RAY AND UV IMAGE DETECTORS

(George Ricker, Mark Bautz and John Doty)

b) Annealing techniques for radiation-damaged Si CCD sensors In previous work carried out by us (M.Bautz and K. Gendreau, private communication), we have measured proton-induced radiation damage in X-ray Si CCDs at dose levels as low as 100 rads (Si). Such damage appears to be due to lattice displacement effects in the buried channel, and therefore is volume dependent. During the past year, we successfully tested a new structure with a "charge viaduct" , which reduced the damage susceptibility of these devices by more than a factor of five.To further reduce the effects of radiation damage, we have recently developed a low temperature (T=113 C) thermal annealing process which is capable of reducing the effects of the damage process in ~10^{-2} of the time over which the South Atlantic Anomally-induced damage accrues in low-earth orbit (i.e. a 1 day anneal period eliminates the effect of damage accrued in 100 days of on-orbit operation).*Combining on-orbit annealing with the "charge viaduct" innovation should effectively result in a "radiation-hardened CCD" with an on-orbit lifetime of >10 years.*

c) Ultra-high resistivity ($\rho > 30000$ ohm-cm) Si CCDs Our research at MIT in developing high resistivity CCDs as X-ray sensors has been extremely successful, resulting in our fabrication of the highest resistivity CCDs yet produced (ρ= 6500 ohm-cm, implying a depletion depth of ~100μm) with a demonstrated quantum efficiency QE > 0.95 at E_x = 5.9 keV. Even higher resistivity CCDs, with depletion depths in the 200-400 μm range, will be required to achieve good performance in the 10-15 keV band, which is in principle accessible with the "next generation" of foil and replica grazing incidence optics (i.e. those which follow Astro-D [~12 keV cutoff; Inoue, private communication] and Spectrum-X [~20 keV cutoff; Schnopper, private communication]). To achieve the desired depletion depths, silicon resistivities of ρ > 30,000 ohm-cm will be required. Recently, we have identified two vendors (a Danish firm [Topsil] and a Soviet supplier) who feel that, with some development effort, they can produce high quality wafer material with resistivities in the 10^4 - 10^5 ohm-cm range.

d) Platinum silicide, room temperature, soft X-ray detector arrays For detection of soft photons in the range 10 eV < E_x < 300 eV, current frontside-illuminated CCDs suffer from problems with Si/SiO_2 gate structure absorption effects (thicknesses ~0.1-1 μm), while backside-illuminated structures suffer from dead layer effects (thickness ~ 0.1 μm). Recently, a new UV detector technology has emerged which promises to provide an *energy-dispersive, solid state array imager* with excellent quantum efficiency in the soft X-ray band. This technology, developed at MIT, is based on platinum silicide (PtSi) Schottky junction Si array detectors, and has produced dead layers as thin as ~0.002 μm, with quantum efficiencies as high as ~60 percent in the mid UV band (Chen, Nechay, and Tsaur 1990 preprint). Dead layer effects should be of little consequence for this new detector. Since the soft X-ray interaction is dominated by the production of hole-electron pairs in the Si substrate, the number of carriers generated is $E_x/3.6$ electrons per eV, so that we expect for the 10-300 eV band to produce a charge packet of ~3-100 electrons per X-ray. This packet size is sufficiently large for *energy-resolved, single photon detection* with the ~1 e- RMS MIT analog electronics systems previously developed for Si CCDs. Furthermore, if we construct the PtSi detector on an n-type Si substrate (rather than p-type, as previously used), the detector dark current should be $\sim 10^{-12}$ pA/cm^2 at *room temperature* (300 K) Thus, this technology promises to provide all the advantages which p-type Si CCDs have provided at higher energies ($1 < E_x < 10$ keV) without the need for supporting cryogenic systems; such a technology is obviously attractive for future soft X-ray missions requiring large focal plane arrays.

ENERGETIC TRANSIENT ARRAY (ETA) FOR GAMMA-RAY BURST ASTRONOMY

(George Ricker)

The Energetic Transient Array (ETA) has been discussed recently by Ricker (1990) as a concept for a dedicated interplanetary network of ~40 microsatellites deployed in an ~1 AU radius solar orbit for the observation of cosmic gamma ray bursts (GRBs). Such a network is essential for the determination of highly accurate (~0.1 arc sec) error boxes for GRBs. For each of ~100 bursts which would be detectable per year of observation by such a network, high resolution ($\Delta E/E$ ~0.2% at 1 MeV) spectra could be obtained through the use of passively-cooled Ge gamma-ray detectors. Stabilization of each microsatellite would be achieved by a novel technique based on the radiation pressure exerted on "featherable" solar paddles, originally developed at MIT in the late 1960's as part of the *SunBlazer* project. Because of the simplicity of the microsats, as well as the economics of mass production and the failure tolerance of such a network of *independent* satellites, a unit cost of ~$250 K per microsat is anticipated. Should such a project be undertaken in the mid 1990's, possibly as an international mission, it should be possible to have a fully functional array of satellites in place before the end of the decade for a total cost of ~$20M, exclusive of launcher fees.

We plan to develop the ETA concept under the proposed new grant program.

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EXPERT SYSTEM FOR ASTRO-D PLANNING AND SCHEDULING

(George Clark, Walter Lewin, Takashi Isobe, and George Ricker)

Discussions during 1989 with members of the Institute for Space and Astronautical Science (ISAS), Japan, raised the possibility of achieving a substantial increase in the efficiency of Astro-D observations through application of an expert system to the tasks of mission planning and scheduling. Such a system, called SPIKE, has been developed and successfully tested for the Hubble Space Telescope by the Space Telescope Science Institute. We are currently in the process of adapting SPIKE to the requirements of Astro-D, and we propose to continue this work in the manner outlined below.

At the present time, the mission planning and scheduling operation carried out at ISAS for

Ginga and the operation originally contemplated for Astro-D require extensive thought and action by human experts, aided by a variety of separate computer planning tools. In the case of Ginga the average rate at which individual proposals are carried out is of the order of one per several days, which is compatible with the scientific requirements of typical Ginga studies and with the maneuvering time between targets. Planning and scheduling for this low rate of observations has been handled satisfactorily by a single scientist. In contrast, Astro-D, like the *Einstein* Observatory, HST, ROSAT, and AXAF, will be capable of useful observations in one or several kiloseconds so that the desirable rate of scientifically distinct observations could be as high as 20 or more per day. Yet preliminary plans for Astro-D scheduling anticipated a maximum rate of only six observations per day set by the inherent limitations of a system that would employ a reasonable number of people in a manner that does not differ fundamentally from the Ginga system. Such a limitation on Astro-D observations would result in a compromised observing schedule whose total scientific yield is substantially less than could be achieved with a truly optimized schedule.

Converting observing proposals into an optimized observing schedule is specially complex for observatories in near earth orbit. The planning and scheduling operation consists of the following tasks:

1) Evaluation of the technical feasibility of proposed observations;
2) Evaluation of their scientific merit and assignment of scientific priority ratings;
3) Planning the required maneuvers of the spacecraft and the configuration of the instrumentation;
4) Scheduling the observations in an optimized mission plan consistent with operational and astronomical constraints.

Constraints include earth occultations, trapped radiation interference, ground station coverage, possible requirements for simultaneous observations by other observatories, minimum sun and moon angles, the schedule of predictable phenomena of the target itself, and provision for inserting targets of opportunity into an existing schedule.

Lacking an efficient computerized planning and scheduling system, valuable observations may be excluded due to the difficulties such constraints impose on the scheduling task. For the ROSAT mission all time-critical observations were placed in a special, very limited, pool requiring extra justification. Under such conditions, short time-critical observations, such as observing predictable eclipse transitions, may have to be turned into scientifically inefficient long observations to avoid dealing with the time criticality issues. Precise determination of the orbital phase of a binary system typically requires only short observations at several carefully determined intervals; such observations may be impossible to implement in an efficient way due to the difficulties of scheduling them. One of the most important objectives of many space-based observing programs is multiple wavelength observations which may require both space-based and ground-based simultaneous observations of the same object. In the past the scheduling of such observations has proven difficult and, indeed, frustrating. It could made much easier if the planning and scheduling system permitted easy inclusion of the constraints of other facilities (e.g. ground-based telescopes can only observe at night). In addition the speed with which a schedule can be revised is an important factor in determining the efficiency and success of a program that depends on the weather over a ground-based observatory. Rapid schedule revision is also important for effective response to extraordinary events such as the SN1987a.

Faced with the crisis of HST mission planning and scheduling that was precipitated by the failures of the SOGS system, Mark Johnston and his associates at the STScI carried out a successful effort to develop an expert system, called SPIKE, for the generation of an optimized mission plan. The concepts underlying SPIKE and its realization in the LISP language have been described by Johnston and his collaborators in recent publications and preprints , e.g. "Artificial Intelligence Approaches to Spacecraft Scheduling" (attached as Appendix A). The system has been developed in a manner that makes it generally applicable to other missions of a similar nature and, incidentally, to the planning and scheduling of ground-based observations.

Given the existence of the SPIKE system as developed at the STScI, the cost/benefit ratio of adapting it to the requirements of the Astro-D mission should be very large. Indeed, we believe that the scientific yield of that mission can be increased substantially at a cost that is a small fraction of the total mission cost. Accordingly, in our grant renewal proposal for CY90 we proposed to port SPIKE to MIT and to adapt it for use in the Astro-D mission. Hale Bradt (PI for the MIT Sky Survey experiment on XTE) and Edward Morgan (Research Scientist on the Sky Survey Experiment) were also eager to explore the application of SPIKE to the XTE scheduling system for which MIT has the project responsibility. Thus SPIKE offered potential advantages for two future X-ray missions with major MIT involvement. During CY90 we have made substantial progress toward the goal of adapting SPIKE to these missions.

Current Status

Using CY90 grant funds we acquired a Sun SPARCstation with a 40 megabyte memory. Mark Johnston has assisted us in porting the 35 MB UNIX-based version of SPIKE to MIT, and it is currently running successfully, as illustrated by Figure 2.2.1 which shows a "Timeline display window" generated by SPIKE operating on the Sun SPARCstation. Takashi Isobe has assumed the responsibilities of systems programmer for adaptation of SPIKE to the special requirements of ASTRO-D, and George Clark is providing scientific guidance. Edward Morgan is providing advice and liaison with the XTE project and with the EUVE project at the Space Sciences Laboratory at Berkeley.

OPTICAL DISK ARCHIVES OF X-RAY DATA

(George Clark, Jonathan Woo, Edward Morgan)

Early in CY90 we reassessed our strategy for achieving our long-term goal of transferring the SAS-3 data archive from its old medium of 2000 1600-bpi tapes to optical disks for long-term storage and efficient access with the SAS 3 analysis systems now operating on the UNIX-based computer network of CSR. In our grant renewal proposal for CY90 we made provision for such an undertaking, but left open the choice of the precise medium and device. Following a review of the options presented by the rapidly evolving commercial technology, we purchased an Apunix Rewritable Optical Disk System that employs a Ricoh 5.25-inch Magneto-Optical Disk Drive with 600 MB cartridges. We have now begun the process of transferring the data archive from 22,000 orbits of SAS 3 data to optical disks. We intend to make a duplicate set of disks for safety.

The value of the SAS 3 archive has been demonstrated by several recent experiences. Following discovery by EXOSAT of the 11-minute orbital periodicity of the X-ray burst source 4U1830-20 in the globular cluster NGC 6624 Morgan et al. (Ap. J. **324**, 851, 1988) used the earlier SAS-3 data to derive an improved value of the period. In a subsequent study (Tan et al. 1990, Ap. J., submitted) the same data were used in conjunction with new Ginga data to establish the likelihood that the source is accelerating toward us, possibly under the influence of the cluster gravitational field. In another area, a recent review study by McCammon and Sanders (Ann. Rev. Astron. Astrophys., **28**, 657, 1990) raised questions about the consistency of results on the soft X-ray background obtained in the three major surveys, namely the Wisconsin rocket survey, and the satellite surveys of HEAO 1 and SAS 3. After an extensive review of the SAS 3 data and analysis, carried out with extensive reference to the old data tapes, the results reported by Marshall and Clark (Ap. J. **287**, 633, 1984) were confirmed and found to be in essential agreement with the other two surveys. Currently, a comprehensive search for evidence of an orbital periodicity in the year-long archived data on the 1975 X-ray nova and blackhole candidate A0620-00 is being carried out by a graduate student as a thesis topic. We anticipate that studies of this kind will become much easier as well as more secure against media failure when the disk transfer is completed.