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THE GROUND SYSTEM FOR THE XUV WIDE FIELD CAMERA ON ROSAT

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In addition to its large X-ray telescope, the W.German ROSAT satellite will carry an XUV telescope (the Wide Field Camera, WFC) provided by the United Kingdom, and covering the wavelength range from 60 to about 600 Å. The primary scientific objective of the mission is to perform all-sky surveys in the X-ray (6-80 Å) and XUV (60-200 Å) wavebands. The subsequent pointing phase will be used for detailed studies of selected sources. I describe the Ground System which will be responsible for WFC mission operations and data handling, and discuss some of the scientific results expectecd from the instrument.

1. INTRODUCTION

The W.German ROSAT satellite (see e.g. [1]) will carry an X-ray telescope (XRT) and a UK XUV telescope (the Wide Field Camera, WFC[1]; see e.g. [2,3,4]), both instruments viewing in the same direction. The primary scientific objective is to perform all-sky surveys, over a six month period, in the X-ray (6-80 Å) and XUV (60-200 Å) wavebands. The subsequent pointing phase will be used for detailed studies of selected sources.

The WFC telescope consists of three nested, gold-coated aluminium mirrors with a microchannel plate (MCP) detector at their common focus. Any one of 8 filters, mounted on an aperture wheel in front of the detectors, can be selected to define the wavelength passbands and suppress geocoronal background radiation which would otherwise saturate the detector count rate. During the survey, 2 different filters will be used, covering the waveband from about 60 up to 200 Å. For pointed observations, additional filters will be available to extend the spectral response to longer wavelengths. The provisional choice of filters is listed in Table 1 together with the expected sensitivity in each passband.

The WFC field of view is five degrees in diameter, reduced to 2.5 degrees for some pointed observations. The spatial resolution is about one arcmin FWHM (full width at half maximum) within about one degree of the optical axis, and for the survey is about two arcmin FWHM averaged over the field-of-view. The location accuracy (error circle 90 per cent confidence radius) for point sources will vary from $\sim$ 1 arcmin for the weakest ones (set by photon counting statistics) to $\leqslant$ 25 arcsec for strong sources (limited by the WFC attitude determination and systematic errors).

During the survey, the viewing axis will scan in ecliptic latitude at a rate of $\approx$ four degrees/minute and in ecliptic longitude at $\approx$ 1 degree/day. Hence, a source will be scanned for up to about a minute every 1.5 hours, over a period of about 5/cos (*ecliptic latitude of source*) days.

ROSAT is scheduled to be launched by a NASA Delta-II rocket in early 1990, into a (nominally) circular orbit at 57 degrees inclination and about 580 km attitude. The Flight Model WFC was delivered to the spacecraft contractor in March 1988.

[1] *The WFC project is supported by the UK Science and Engineering Research Council (SERC) The WFC instrumentation and the Ground System for WFC mission operations and data processing are being developed by a consortium of five UK institutes University of Leicester, SERC's Rutherford Appleton Laboratory (RAL), the Mullard Space Science Laboratory–Universtiy College London, University of Birmingham and Imperial College of Science and Technology–London*

This paper describes the Ground System which is being developed for WFC mission operations and data handling, and discusses some of the scientific results which may be expected from the instrument.

2. IN-ORBIT OPERATION OF ROSAT

Control of ROSAT and reception of telemetry data will be handled by the German Space Operations Centre (GSOC) at Oberpfaffenhofen near Munich, using its nearby ground station at Weilheim. The spacecraft will be in contact with the ground station for about eight minutes on six consecutive orbits each day. The ROSAT telecommand uplink rate will be 1 kbit/s, equivalent to about 10 (24-bit) commands per second, with a daily uplink requirement of several thousand commands per day. Most of these commands are 'time tagged' and are put into on-board deferred command stores to enable the operation of the satellite to continue when out of ground contact. The data stored on-board on tape recorders ('stored data') will be telemetered from ROSAT to the ground station at a rate of 1 Mbit/s, with a daily volume of about 800 Mbit. There is a second telemetry channel of 8 kbit/s which conveys (mainly) housekeeping data in real-time.

During each ground contact the critical 'housekeeping' parameters will be checked in real-time at GSOC, and the stored data will be recorded at Weilheim for retransmission, via dataline, to GSOC after the contact. The computers at GSOC will then carry out the basic data processing such as sorting the data, determining the orbital elements and computing the spacecraft attitude. For 'near-real-time' checkout, all stored XRT and WFC housekeeping and calibration data will be copied out from the telemetry

Table 1. ROSAT WFC Filters, Wavebands and Sensitivity.

Filter Type [a]	Survey (S) or Pointed (P)	FOV Diam. (deg.)	'Mean' Wave length	Bandpass (Å) (at 10% of peak efficiency)	Point-source Sensitivity (μJy) [b]
C/Lexan/B (×2)	S + P	5	100 (Å)	60-140	1.0
Be/Lexan (×2)	S + P	5	140	112-200	1.4
Al/Lexan	P	2.5	180	150-220	7.3
Sn/Al	P	2.5	600	530-720	~220
TBD	P	2.5	TBD		

[a] An eighth filter is an interference type for use with the WFC UV calibration source
[b] For 5σ significance, exposure time of 2000 s (a typical value for each filter for the survey and for pointed observations) and 'typical' background

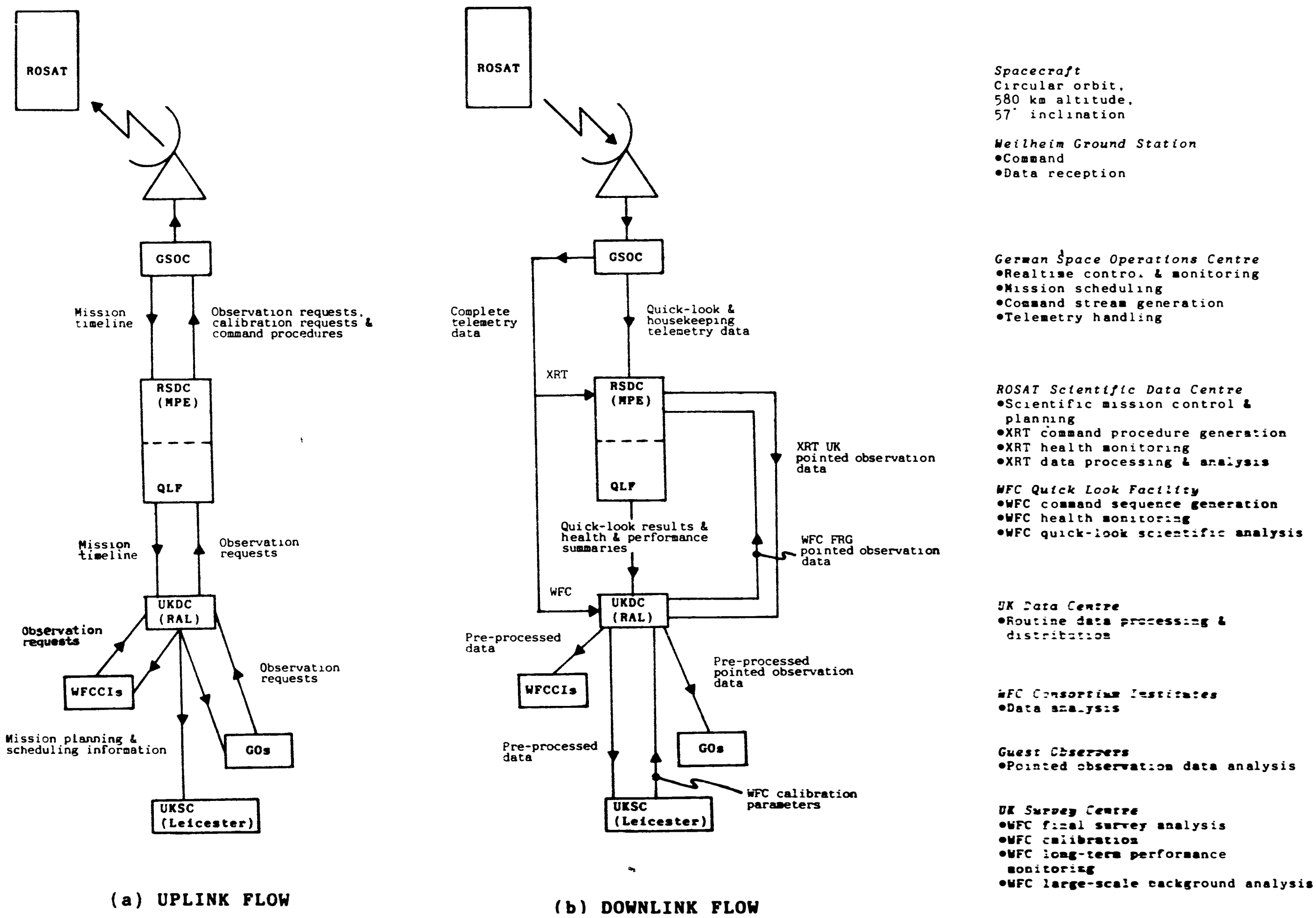

Fig 1. ROSAT WFC Ground System· data flow between sites. (a) The main flow of information for controlling the satellite. (b) The main flow of data received from the satellite.

stream at the ground station and transmitted as soon as possible over the data line from GSOC to the ROSAT Scientific Data Centre (RSDC) at the Max Planck Institut für Extraterrestrische Physik (MPE), Garching near Munich. In addition, three orbits per day of stored XRT and WFC housekeeping and science data ('quick-look data') will be transmitted over the data line from GSOC to the RSDC, within a few hours of ground reception. The final, complete data tapes are expected to be available from GSOC within about a week of ground reception.

3. THE GROUND SYSTEM

The WFC Ground System comprises the necessary hardware, software, manpower, operational procedures and documentation for handling of all WFC observations and for the UK share of XRT pointed observations. The Ground System is responsible for:

- Generation of WFC command procedures.
- Monitoring WFC status, health and performance.
- Analysis of WFC all-sky survey data to produce a catalogue of XUV sources.
- Pointed observations:
  - Administration of UK observation requests within UK.
  - Processing, distribution and analysis of data from WFC observations.
  - Distribution and analysis of data from UK XRT pointed observations.

3.1 WFC Ground System Sites

The main elements of the WFC Ground System are:

- **WFC Quick Look Facility (QLF)**, at the ROSAT Scientific Data Centre (RSDC), MPE, Garching – for WFC command procedure generation, WFC health monitoring, quick-look analysis of WFC data, and acting as the WFC Consortium interface with GSOC and MPE for mission operations (see [5]).
- **ROSAT UK Data Centre (UKDC)** in the UK, at RAL – for routine processing and distribution of WFC survey and pointed observation data.
- **ROSAT UK Survey Centre (UKSC)** in the UK, at Leicester University – for full and long-term health and performance monitoring of the WFC, WFC calibration, final survey analysis, and large-scale background analysis.
- **WFC Consortium Institutes (WFCCI)** – for analysis of survey and pointed observation data.

The data flow between Ground System sites is shown in Figure 1.

3.2 Ground System Organisation and Operations

All the Consortium Institutes are participating in the development of the WFC Ground System; similarly, they will all participate in the data analysis and provide manpower for WFC mission operations. Each site within the WFC Ground System has one person to coordinate the work there and to act as the formal interface for that site. In addition, a UK Ground System Manager coordinates the overall development and operation of the whole system (ie. QLF, UKDC, UKSC, WFCCIs, and interfaces to GSOC, RSDC and Guest Observers). Scientific direction and management of the WFC project is under the control of a Project Steering Group comprising the Principal

Investigator, Co-Principal Investigators and other persons co-opted as required. Reporting to the Steering Group, and chaired by the UK Ground System Manager, a WFC Ground System Working Group is responsible for directing software development and operations for the Consortium. Included in these tasks are the definition, design, production, integration and test of software, and the training and procedures needed for operations. The working group holds regular progress meetings, every six to eight weeks.

3.3 Specifying and Planning the Ground System

In deciding on an appropriate level of formal documentation for specifying the WFC Ground System a balance has had to be achieved between having sufficient documentation to meet the needs of the distributed nature of the project (both nationally and internationally), particularly with regard to the large number of interfaces, and the limitations on the manpower available to produce and maintain formal specifications and plans. The adopted solution follows in general terms the *ESA Software Engineering Standards* [6]. At the top level is the Functional Requirements Specification and Project Plan, which defines in broad terms: (i) the tasks to be performed at each Ground System site, (ii) the requirements on computer hardware and software, (iii) the organisational structure for the development and operations. At the next level are:

- **Interface Control Documents.** These specify the interfaces with GSOC and the RSDC.
- **Software Requirements Specification.** This specifies the software required for each package (see below). At a lower level is the Software Design Specification, which describes the design of each package, including a functional description of each program and inter-program and inter-package file specifications; it also contains the software standards specification. At the lowest level, program listings will contain a basic description of individual programs and subroutines; much of this text can be automatically extracted to form lists of routines and associated interface information.
- **Integration and Test Plan.** This specifies how individual packages are to be tested and integrated as part of the overall Ground System. At a lower level, Software Test Plans and Reports will be produced for each package. Similarly, Site Integration and Test Plans and Reports will cover the integration of individual packages at each site.
- **Operations Plan.** This specifies operations procedures for the whole WFC Ground System. At a lower level are the Site Procedures Manuals giving detailed operations procedures for each site, and the Observer's Manual and Science Analysis Software User Manual.
- **Schedule and Resources Plan.** This specifies: (i) the overall schedules for the development and operation of the Ground System, (ii) the schedules for development of each software package, and (iii) the manpower resources committed by each Consortium institute.

3.4 Software Development

The data reduction and analysis software is being developed jointly by the five institutes in the WFC consortium. At an early stage in the software development programme the tasks were divided into modular packages and each institute given responsibility for one or more packages, taking account of previous experience in similar areas. In addition, use is being made of existing software where possible. The interfaces between packages were defined very carefully and subsequently put under a change control procedure. Software portability has not been a significant problem since all those involved in ROSAT are using VAX computers running under the VMS operating system. The VAX computers of the WFC institutes are all inter-connected via the UK Joint Academic Network (JANET) which is used very heavily for file and mail transfers, and forms an essential link.

Program coding standards were also established at the outset: programs are written in ANSI Fortran 77 with certian restrictions but with a few extensions allowed. All of these extensions appear in a similar form in the current draft of Fortran 8x.

Software for the initial reduction stages, up to and including the conversion of photon events into images, is specific to the WFC and the data files use ordinary VMS file structures. The scientific analysis software will be designed to form part of the Starlink *Asterix* package) [7] which was developed to handle data from ESA's *Exosat* X-ray astronomy satellite. This package is now beng converted to run under the new Starlink Software environment called ADAM. All files produced by the *Asterix* package will use the Starlink Hierarchical Data System (HDS). HDS structures are open-ended and self describing; this makes them particularly suitable for storing scientific data. If large arrays (such as images) are stored in HDS files they may also be accessed via the VMS mapping mechanism.

3.5 The Software Packages

The twelve software packages, and the division of responsibilities, are as follows:

1. **General Data Handling at the UKDC** – for receipt and validation of the data at the UKDC, for archiving and retrieval of data, and for selection and distribution of the processed data. *(RAL)*
2. **Status and Health Monitoring** – for analysing the WFC housekeeping data to monitor instrument status and health. *(MSSL with ICST)*
3. **Calibration and Performance Analysis** – for analysing the WFC science data to monitor the instrument performance and to derive instrument calibration data. *(ICST with Leicester)*
4. **Attitude determination** – to determine the WFC attitude, and to monitor the WFC Star Tracker performance. *(RAL)*
5. **Event Processing** – pre-processes the data from the WFC detector events into a suitable form for distribution, and converts them from raw detector coordinates to celestial coordinates by applying the instrument calibration and attitude solution. *(Leicester)*
6. **Science Data Analysis** – for scientific analysis of the WFC and XRT observations. (*Birmingham with Leicester and ICST)*
7. **Production of the Final Source Catalogue** – for analysis of all the data from the survey phase in a uniform manner, to produce the final XUV source catalogue for publication. The software will be built up from that in the Event Processing and Science Data Analysis packages. (*Leicester*)
8. **Generation of Test Data** – necessary for system verification from simulations and from instrument test data. *(Leicester with MSSL and RAL)*
9. **Mission Analysis** – for monitoring the progress of the mission and for planning pointed observations. *(RAL)*
10. **Pointed Observation Programme** – for the administration of the pointed observation prog-

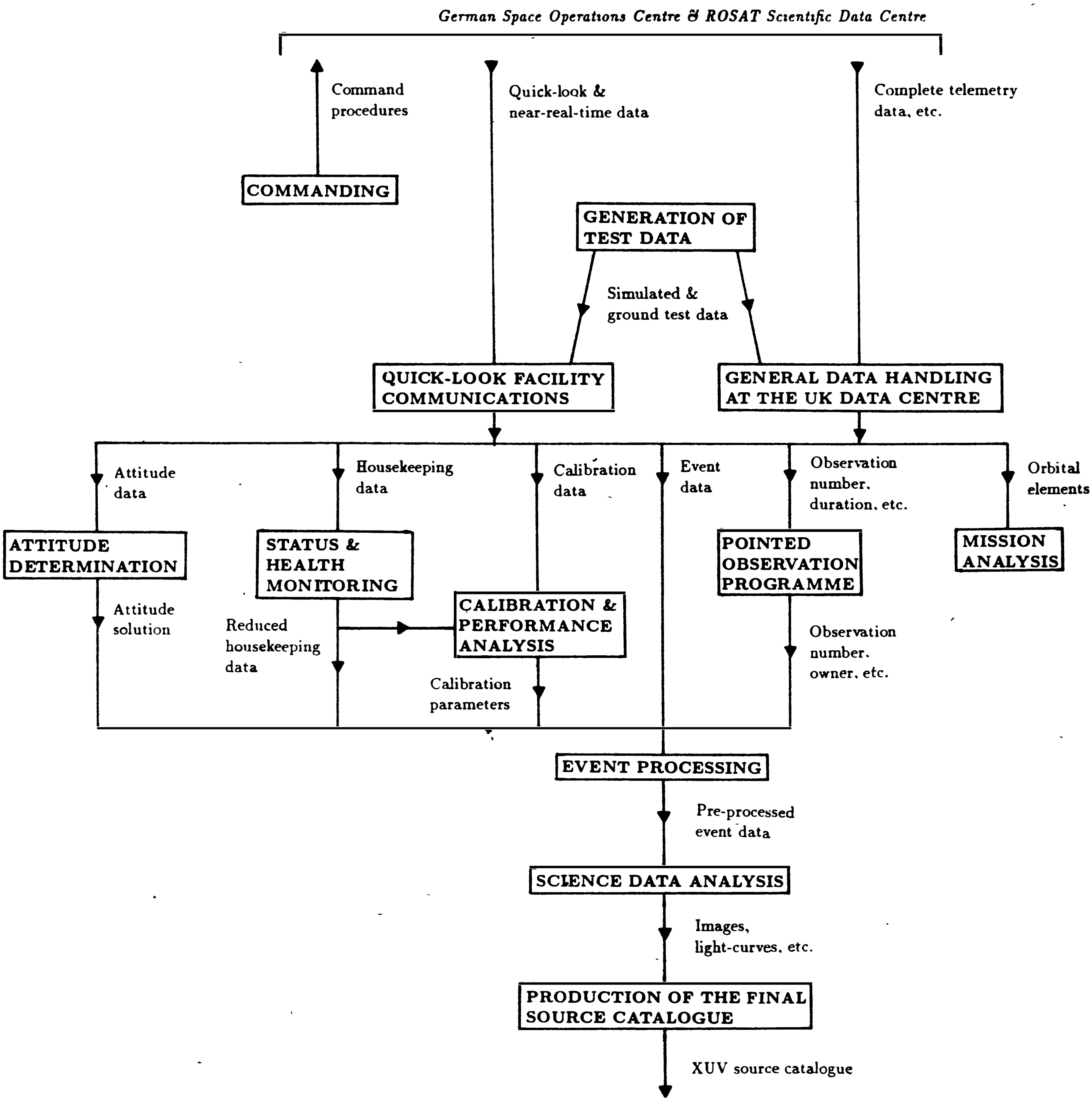

Fig. 2. Logical relationships and data flow between the software packages. For clarity, the scheme is shown here in a somewhat simplified form.

ramme. Databases will contain details of observation proposals and accounting information on observations. *(RAL)*

11. **Commanding** – required at the QLF for generating, checking and amending command procedures for the WFC. *(MSSL)*
12. **QLF Communications** – allows the QLF computer to communicate with the computers at MPE and GSOC, for transmission of WFC command procedures and reception of 'near-real-time' and 'quick-look' telemetry data. *(MSSL)*

Figure 2 shows in a schematic manner the relationships and data flow between the packages.

4. SATELLITE CONTROL

The flow of information through the Ground System and to the satellite is shown schematically in Figure 1a. As already mentioned, operation of the spacecraft and scientific payload will mostly be achieved using deferred commands. These commands will be generated at GSOC in a largely automatic manner from information contained in the *Mission Time Line*, and using pre-defined command procedures. The Mission Time Line will consist of a time-ordered list of events – either ones to be performed by the spacecraft (e.g. attitude changes) or by the scientific instruments (e.g. set filter position, set measurement mode, perform on-board calibration), or ones determined by the orbit geometry (e.g. radiation belt passages, ground contacts). The Mission Time Line will be generated from information contained in *request forms* for pointed observations, survey observations and on-board calibrations/tests, together with general constraints on the mission (e.g. location of the radiation belts, minimum

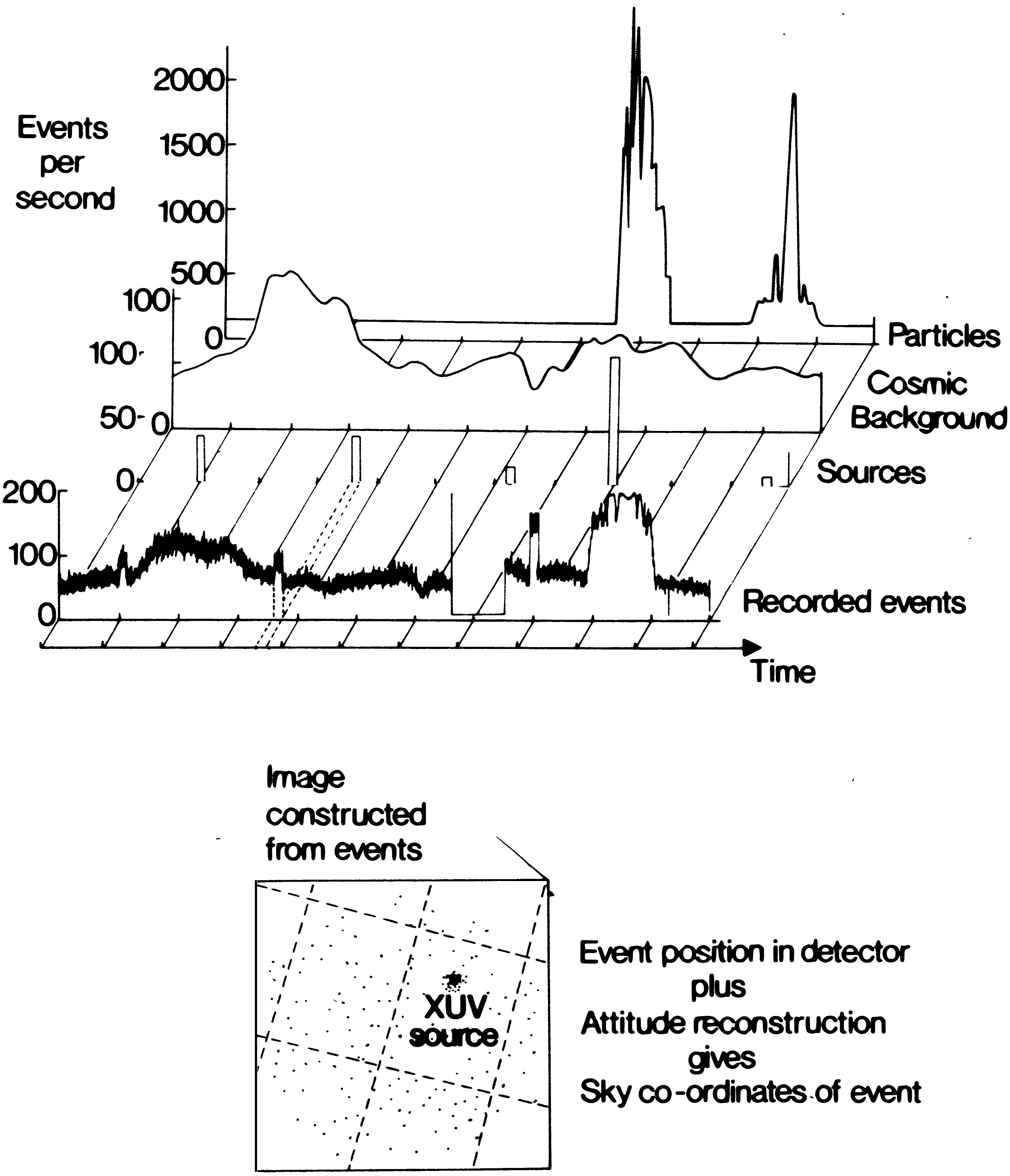

Fig. 3. Simulation of WFC data from one orbit of ROSAT during the survey. In the histograms of count rate versus time, the counts have been summed over the WFC field-of-view, and the time axis is equivalent to ecliptic latitude. The inset indicates how sky maps are constructed from the detected events.

permitted viewing angle to the Earth when performing an observation). For example, for each pointed observation that is to be performed there will be an observation request form stating the requirements, e.g. celestial pointing position, exposure time, instruments and wavebands, any special time constraints.

The WFC deferred command store has a capacity of 255 commands, sufficient for at least a day of normal operations.

5. PROCESSING OF THE SCIENCE DATA

The primary aims of the data analysis are: (i) to produce from the WFC survey data, a catalogue of fluxes and celestial positions of 'point-like' XUV sources; and (ii) to provide a flexible system for interactive analysis of WFC data from pointed observations and the survey, and of the UK share of XRT pointed observation data.

The coordinates and arrival times of the *events* registered by the focal plane detector will form the primary scientific data from the WFC. Besides photon events, there are 'background' events caused by charged particles etc. The raw telemetry data from the WFC will occupy ~50 Mbyte/day, i.e. ~10 Gbyte for the six month all-sky survey and ~20 Gbyte per year of pointed observations.

5.1 All-Sky Survey

During the scanning phase the WFC is expected to pro-

duce an average of ~100 events/second for six months. Effectively, these have to be sorted into a fixed frame and imaged with a resolution of better than 1 arcminute. In total this means that some 1.6×10^9 events have to be sorted into a set of $\sim 3 \times 10^8$ pixels. This will be handled be dividing the celestrial sphere into a coarse grid along lines of ecliptic longitude and latitude with a spacing of about 3 degrees. The attitude of the instrument, computed from star-tracker data, will be used to sort each incoming photon into the appropriate celestial cell. The original (instrument) coordinates of each photon event are preserved; a set of linked lists is used, one for each celestial cell, the whole structure being stored on a random-access file. One such file will be produced at the UK Data Centre for each day of operations; this will be distributed to the Consortium institutes for analysis.

As the survey observations proceed, the data will be analysed in the UK with a time lag of about 2 weeks. Each Consortium institute will receive all the WFC data but will have the prime responsibility for the analysis of a different region of the celestial sphere. The first operation will be to merge data from the current day with the data base which has accumulated events collected earlier in the survey. Each linked list will be merged with the linked list for the corresponding celestial cell in the data base. The scan path advances in ecliptic longitude by 1 degree day, so that a new strip of sky will be available for analysis every few days. The data for this strip will be contained in a small number of cells, i.e. linked lists, on the data base. After analysis these lists can be archived and the disc space released for re-use by a garbage collection phase. The analysis of each strip of sky will proceed by forming images and searching these for sources. The exposure time of each detected source will be computed, and the flux derived. A time-series may be extracted from the data for the stronger sources. A source on the ecliptic will be scanned some 80 times over a five-day period; those at higher ecliptic latitude will be in the field of view for rather longer. Small regions around each ecliptic pole are likely to be scanned for the whole of the survey period and will be treated specially in the analysis.

Since it is unlikely that a uniform survey analysis at maximum sensitivity will be possible while the survey data are still being accumulated, it is planned to perform a re-analysis of the complete survey database after the end of the survey phase of the mission and following review of the experience gained during the previous analysis.

In order to monitor the general progress of the survey, the QLF will analyse a small fraction (~ 20 per cent) of the data within about a day of the observations being made [5].

5.2 Pointed Observations

The pointed phase processing will be somewhat simpler: the incoming events will be sorted into data-sets structured with a 'small-map' scheme along the lines of those used by *Einstein* and *Exosat*; these pointed observation data-sets will be compatible with those described above for the survey data. A software package will be provided so that users can form images and extract temporal and spectral information. Since UK observers will have access to both the XRT and WFC simultaneously for a proportion of the pointed phase, the software must be able to analyse data from both instruments in a uniform manner.

5.3 Generation of Test Data

Pre-launch data to test the Ground System software are available from two sources: (i) the WFC instrument, (ii) a software scientific data simulator. The latter is also used to predict background count rates and exposure times. Figure 3 shows an example of survey data for one orbit, generated by the simulator.

5.4 Handling of Calibration Data

Instrument calibration data, derived both from pre-launch laboratory measurements and in-orbit observations, have to be available in suitable form to the scientific analysis programs. In-orbit calibrations will use both observations of selected celestial targets and an on-board calibration system. The latter system projects, from a mounting rigidly locked to the mirror assembly, a rectangular array of about 100 fiducial spots on to the focal plane detector, to allow linearisation of the electrical read-out of the detector and correction for any relative movement between detector and mirror assembly. Any method of handling the derived calibration data must allow both for parameters which vary with time and for improved knowledge of parameters as the mission progresses. These requirements are being met by use of HDS, which provides a flexible system for storing, updating, enlarging, deleting, retrieving, or altering the form of any particular subset of the data.

6. PREDICTED NUMBERS OF SOURCES

A severe restriction on the visibility of sources at XUV wavelengths ~100–1000 Å is the attenuation of the radiation by photoelectric absorption in the interstellar medium or intrinsic to the source. due to the very limited observations so far made in the XUV band, any predictions of numbers of sources observable by the WFC will have large uncertainties. However, it is useful for mission planning purposes at least, to have some rough estimates. The two major contributors to the XUV source detections are expected to be cool stars and hot white dwarfs, with each yielding $\gtrsim$1000 sources in the all-sky survey, giving the potential for detailed statistical studies.

Pye and McHardy [8] have discussed cool star observations with the WFC. The maximum distance at which quiescent emission from main sequence stars is expected to be detected is about 25 pc. At this distance, absorption by the interstellar medium is still expected to be low and the limiting factor is simply the low intrinsic luminosity of these objects. RS CVn systems, with their higher luminosities, are expected to be observable out to at least 100 pc, where interstellar absorption may well be significant. The WFC is expected to detect $\gtrsim$ 1000 cool main sequence stars. The apparent magnitudes (m_v) of main sequence stars at a distance of 25 pc are [9]: FO–4.6, F5–5.4, GO–6.4, G5–7.1, KO–7.9, K5–9.3, MO–11.0, M5–13.8. The corresponding surface densities (stars per 4π steradians) are: F–200, G–400, K–650, M–3300. Hence, for each spectral type, we would expect to detect in the WFC survey about 50 per cent, 30 per cent, 30 per cent, 20 per cent respectively of the total numbers of these stars in the volume out to 25 pc.

Barstow and Pounds [10] have predicted the numbers of hot white dwarfs detectable by the WFC. For a white dwarf of a given temperature, the WFC is much more sensitive to a H-dominated stellar atmosphere than to one dominated by He. Hot white dwarfs are sufficiently luminous in the XUV to be potentially observable out to distances approaching several kpc. However, it is likely that in practice, photoelectric absorption in the interstellar medium will largely determine the viewing horizon. The WFC is expected to detect ~ 2500 white dwarfs during the all-sky survey. A total of approximately 1500 white dwarfs is presently known, of which about 30 per cent have temperatures to which the WFC is sensitive. Comparing this figure with the number of white dwarfs that the WFC is expected to see, shows the value of the all-sky XUV survey for statistical analyses.

7. CONCLUSION

I have described the Ground System which will be responsible for WFC mission operations and data handling. Both in development and for operation a *distributed* approach is being adopted to provide the necessary manpower and resources to accomplish the task, and following the example of the WFC instrument development which has already been done successfully on a consortium-wide basis.

The system must be able to handle a WFC data flow of about 50 Mbyte/day over a period of several years. The Quick Facility in Munich will enable close liaison with GSOC and the ROSAT Scientific Data Centre, and will allow rapid monitoring of the instrument data. The UK Data Centre will perform routine pre-processing, archiving and distribution of data. The UK Survey Centre is responsible for several long-term scientific tasks including final analysis of the WFC survey data. The Consortium institute sites will all be equipped to perform full scientific analysis of the observations and hence allow maximum participation by Consortium staff. In addition, the scientific data analysis software will be available to guest observers.

ACKNOWLEDGEMENTS

The WFC instrument and ground system design and development are the responsibility of the many WFC personnel at the Consortium institutes. I thank J. Daniels (Leicester) and M. Ricketts (RAL) for Figure 3, and C. Page, M. Watson (Leicester) and A. Harris (RAL) for valuable comments and suggestions.

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THE ROSAT WIDE FIELD CAMERA XUV TELESCOPE

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If all goes to plan early 1990 will see NASA launch the West German X-ray astronomy satellite ROSAT. On-board will be the main X-ray telescope designed to view the energy range 0.15 to 2.0 keV while alongside will be the XUV Wide Field Camera built by the United Kingdom to cover the lower energy band 0.062 to 0.21 keV. The prime objective of the mission is to perform an all-sky survey of soft X-ray sources with a sensitivity much better than has previously been possible and an energy band extending into the extreme ultraviolet, a region of the electromagnetic spectrum which has so far remained largely unexplored.

1. XUV ASTRONOMY

Before 1975 the possibility of observing the sky in the XUV energy ($\approx$ 0.04–0.25 keV) band lying between the ultraviolet and X-ray regions of the spectrum, seemed remote. Even after escaping the atmospheric absorption of the Earth by placing a telescope on a sounding rocket or satellite the absorption of XUV photons by the interstellar medium was thought to be too large for even the brightest stellar sources to penetrate. However, an experiment on the Apollo-Soyuz mission 1975 (Bowyer *et al*, 1977) made the first detection of a non-solar XUV source, the hot white dwarf HZ 43, and recent estimates of the interstellar absorption (Paresce, 1984) indicate that there exist 'holes' through the interstellar medium which should provide a window for XUV astronomy. Unfortunately designing and building telescopes to detect and image XUV radiation is not easy. As in the neighbouring X-ray band, XUV will not reflect off mirrors at normal incidence and grazing incidence optics must be used. Very thin filters can be made to define windows in the XUV by blocking unwanted UV background radiation but they are difficult to make and extremely sensitive to vibration expected at launch. Detecting XUV with high efficiency is not easy either. Only recent developments of XUV sensitive photo-cathodes and photon counting-imaging devices have made the design of a suitable detector possible.

XUV radiation dominates the spectrum from regions with temperatures in the range 3×10^4 to 1×10^6K and therefore the astronomical objects likely to be of interest include hot degenerate stars, coronae of cool stars, dwarf novae and faint extended objects such as supernova remnants and clusters of galaxies. Observation of the diffuse XUV background and line of sight column densities will also provide information about the local interstellar medium. At present only a handful of XUV sources are known. However, it is hoped that an all-sky survey performed with the WFC will provide a much larger catalogue of sources including about 1000 main sequence stars and 2500 white dwarfs. Follow-up pointed observations will provide further information with which to probe the environment in these and other objects.

2. THE WIDE FIELD CAMERA INSTRUMENT

The WFC and its individual components have been discussed in much detail in other publications (e.g. Barstow *et al*, 1985b). Consequently, we will give here just a brief description of the hardware and concentrate on the scientific performance.

Figure 1 is a cutaway drawing of the WFC showing the main optical components – grazing incidence mirrors, filters and microchannel plate (MCP) detectors. A nested set of three Wolter-Schwarzschild Type I mirrors (see Willingale *et al*, 1987), fabricated from aluminium and coated with gold for maximum reflectance provide a geometrical collecting area of 475cm^2 with a common focal length of 525 mm. The grazing incidence angles chosen (typically $\approx$ 7.5 degrees) allow the collecting area to be optimised whilst retaining a wide (2.5 degree radius) circular field of view and a low energy reflectivity cut-off at 0.21keV. To obtain a high quality image and good reflectivity, the surface of each mirror must be incredibly smooth and accurately figured. A surface finish of 9Å rms for scale lengths less than 100μm and 45Å rms for scale lengths less than 1mm has been achieved. The profile of any mirror does not deviate from the required form by more than 1μm over its axial length or depart from circularity by more than 12μm across its diameter (60cm for the largest element). An on-axis resolution of $\approx$ 2.3' half energy width (HEW) has been measured but the response degrades to $\approx$ 4.4' HEW at 2.5 degrees off-axis due to optical aberrations inherent in the telescope design. Hence, the average resolution for the survey will be $\approx$ 3.5' HEW.

In order to take full advantage of the telescope resolution the pair of MCPs in the detector are both curved like a watchglass to match the optimum focal surface, as is the resistive anode readout system (see Barstow *et al*, 1985a). A CsI photocathode is deposited directly onto the front face of the front MCP to enhance the XUV quantum efficiency. The detector resolution is substantially (a factor > 2) better than that of the mirror nest and consequently does not ccontribute significantly to the net response of the WFC. A focal plane turntable can be used to select one of two identical detector assemblies in flight.

The filter wheel assembly contains eight filters, any one of which can be selected to define the energy passbands and suppress geocoronal background radiation which would otherwise saturate the detector count rate. Filters also prevent the detection of UV radiation form hot O/B0 stars which would otherwise be imaged indistinguishably from XUV sources. There are four large diameter filters (5 degrees field of view) for the survey (S)

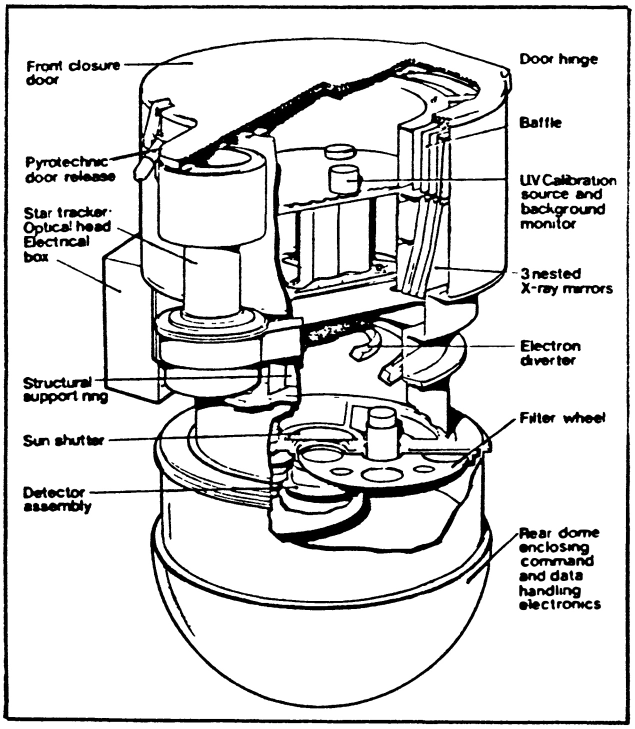


Fig. 1. Cutaway diagram of the WFC showing its principal optical components.

and three small diameter (2.5 degrees field view) for pointed (P) observations. S filters will also be used in the pointed phase of the mission. To have high transmission in the XUV all of these filters have to be extremely thin, amounting to no more than a few thousand Å of the materials from which they are constructed (see Table I). A UV calibration system, mounted on the mirror support, permits in-flight monitoring of detector gain drifts and thermally induced misalignment of the telescope axis. One position in the filter wheel is occupied by a UV interference filter for use with this system.

The WFC is sensitive to particle background, particularly soft electrons. A high percentage of incident electrons (≈ 97%) are deflected away from the detector aperture by a magnetic diverter. However, the remaining particle flux can still be significant. Two particle detectors, a geiger tube and a channel electron multiplier (CEM), monitor this background and the former can provide a signal to switch off the MCP detector during passage through high background regions (ie. South Atlantic Anomaly, Auroral Zones). The CEM may be used, in conjunction with an 'opaque' filter (ie. one that excludes all radiation but the particle flux) mounted in front of the MCP, to establish the electron contribution to the total observed background. This is important if we wish to study the diffuse XUV background, and therefore the local interstellar medium, since the electron flux is not well determined and also exhibits large temporal variations. Studies of the electron background expected in the WFC have not yet established the feasibility or necessity of the technique but an opaque filter would occupy one of the P filter slots.

Table 1 summarises the main performance characteristics of the science filters and Figure 2 shows the effective area of the WFC for each XUV filter design.

3. INTERSTELLAR ABSORPTION

Attenuation of the incident flux from a source by the ISM is extremely important in the XUV because most elements have electron binding energies in the range 10-100eV. Cruddace *et al* (1974) have calculated the effective interstellar absorption cross section (σ) per H atom in the

Fig. 2. The effective area of the WFC for each filter: [a] C+B+Lexan, [b] Be+Lexan, [c] Al+Lexan and [d] Sn+Al.

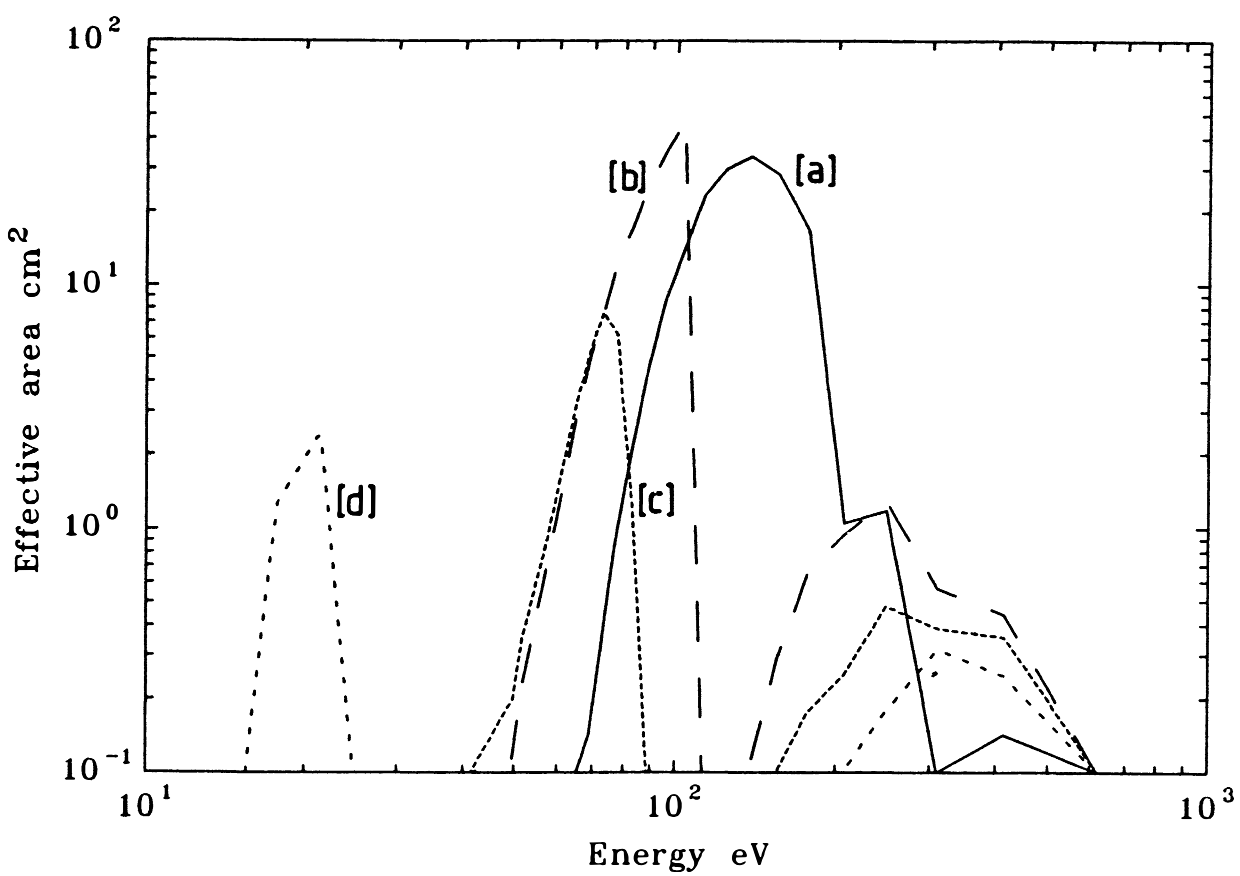


Table 1. ROSAT WFC filters, wavebands and sensitivity.

Filter Type [a]	Survey (S) or Pointed (P)	FOV Diam. (deg.)	'Mean' Energy (eV)	Bandpass (eV) (at 10% of peak efficiency)	Point-source Sensitivity [b] (μJy)	(HZ43^{-1})
C/Lexan/B (×2)	S + P	5	124	90-210	1.0	3000
Be/Lexan (×2)	S + P	5	90	62-111	1.4	7000
Al/Lexan	P	2.5	69	56-83	7.3	1400
Sn/Al [b]	P	2.5	20	17-24	220	185

[a] Provisional. [b] For 5σ significance, exposure time of 2000 s (a typical value for each filter for the survey and for pointed observations) and 'typical' background. The right hand column expresses the sensitivity in terms of the flux from the white dwarf HZ43, the brightest known XUV source.

Table 2. WFC Passbands: Absorption of XUV Radiation by the ISM.

Wavelength (ev)	ISM Effective Cross-section ($10^{-20}cm^2$) [a]	ISM Effective Hydrogen Column Density ($10^{19}cm^{-2}$) for unit mean free path	Mean Free Path (pc) [b]
124	3.2	3.1	190
90	7.8	1.3	70
69	15.0	0.7	35
20	200	0.05	2.3

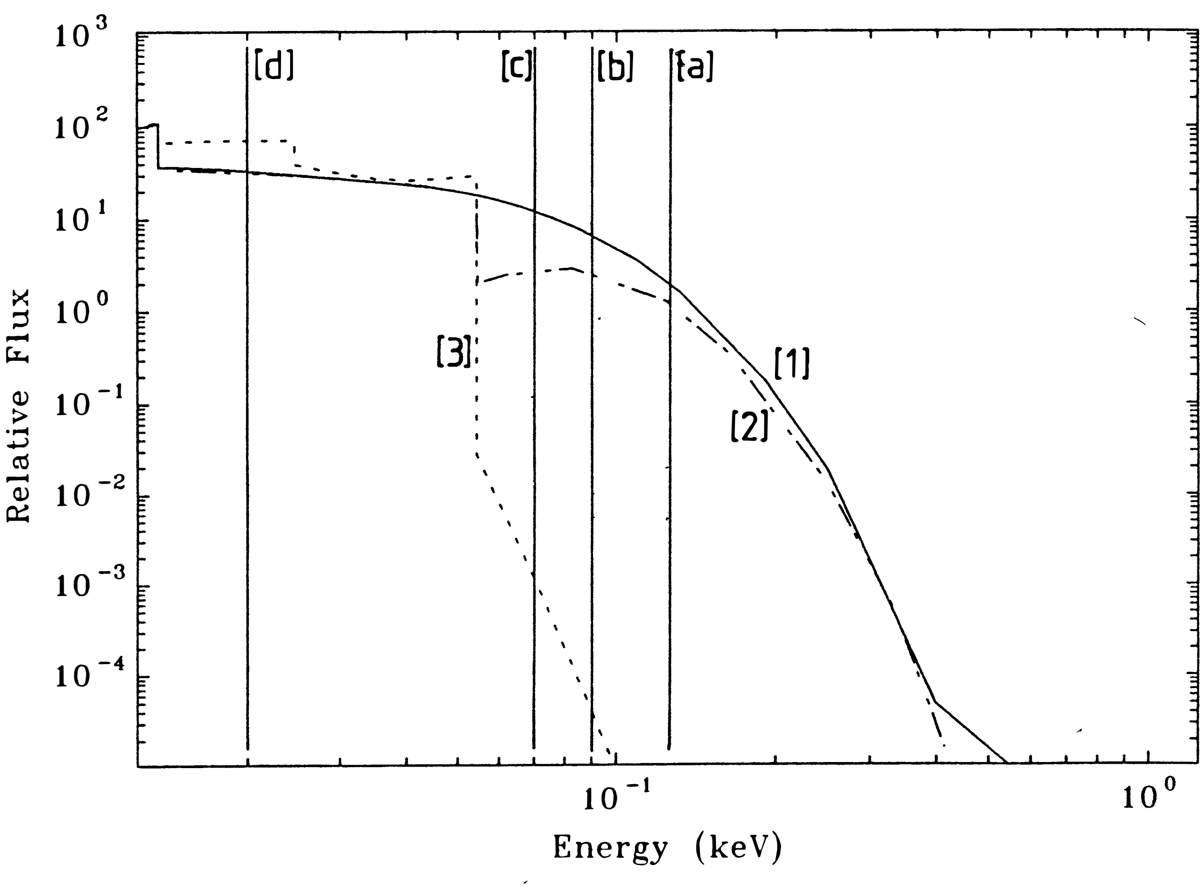
[a] From Cruddace *et al* (1974). [b] for ISM with constant volumn number density of neutral hydrogen of 0.07 cm^{-3} (Paresce 1984).

range 6eV to 1.24keV from the weighted sum of all individual components. Absorption in the XUV is dominated by H and He and is a steep function of wavelength, increasing by a factor ≈ 500 from 124eV down to the Lyman edge at 13.6eV. To some extent source visibility will be dependent upon the intrinsic spectrum. However, a good general indication of the limitations of the absorbing matter can be obtained by calculating the effective column density for unit photon mean free path (MFP) at the mean wavelength of each pass band and the MFP for a mean local density of 0.07 atoms cm^{-3} (see Paresce, 1984; Table 2). In reality, as demonstrated by the data of Frisch and York (1983) and Paresce (1984), there are large variations in the line of sight column density with direction through the galaxy. Although when looking out of the galactic plane data is sparse and the column density/distance poorly determined, the integrated HI column density through the galaxy (Heiles and Jenkins, 1976) may be low enough ($<10^{20}cm^{-2}$) to see through at high latitudes.

4. OBSERVING HOT WHITE DWARFS

Sion (1986) has recently reviewed our current understanding of the formation and evolution of white dwarfs (WDs). It is clear that there are many problems concerning the relationships between different kinds of WDs still to be understood. An unbiased survey of the higher temperature stars is fundamental in answering some of these questions. Most stars can be divided into two broad sub groups, those whose atmospheres are dominated by H and those where He is the main constituent. Some stars may contain significant fractions off CNO metals (eg. PG1159 objects) but their abundances are not well determined as yet, although some model atmospheres do exist for solar abundances (Hummer and Mihalas, 1970). Figure 3 shows the intrinsic spectra for a 60000K WD (log g ≈ 8), having an atmosphere ranging between the extremes of pure H (Wesemael *et al*, 1980) through a homogeneous He/H mixture (Petre *et al*, 1984; He/H = 10^{-4} in this case) to pure He (Wesemael, 1981). The mean ener-

Fig. 3. White dwarf model atmospheres for a 60000K star comprising [1] pure H, [2] He/H=10^{-4} and [3] pure He. The solid vertical lines indicate the mean energies of each filter, designated as in figure 2.



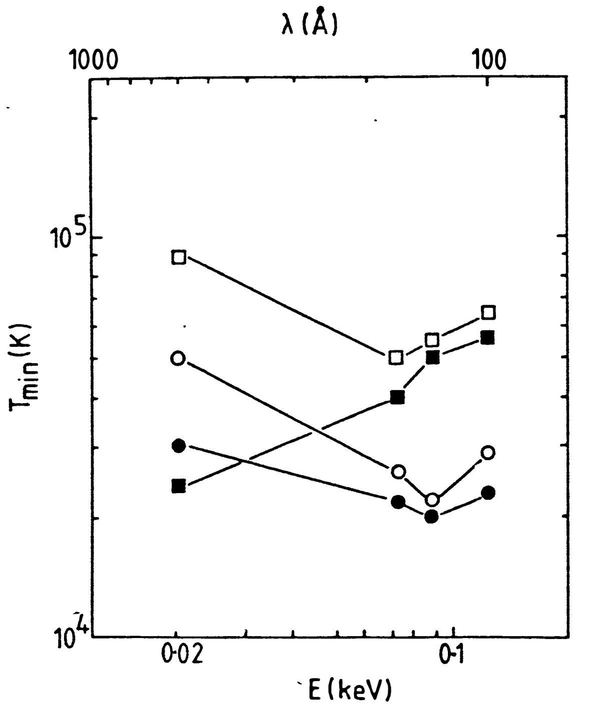


Fig. 4. The minimum white dwarf temperature to which the WFC is sensitive as a function of photon energy and wavelength. The circles represent a pure H atmosphere and the squares a pure He atmosphere Filled and open shapes are for column densities of 10^{18} and 10^{19} respectively

gies of the WFC bands are marked for comparison. Clearly, the WFC survey is much more sensitive to H dominated stars of given temperature than for those with He, as would be expected given the relatively high He opacity at higher energies. The relative sensitivity of each filter to atmosphere and column density is illustrated in figure 4, where the minimum detectable temperature (T_{min}) is displayed as a function of the mean energy for each band pass. As might be expected, T_{min} for the three highest energy filters is fairly insensitive to column but shows a marked increase for the transition from a pure H to a pure He atmosphere. The reverse is true at the lower energy although a high column density increases the size of the T_{min} gap between the atmospheres.

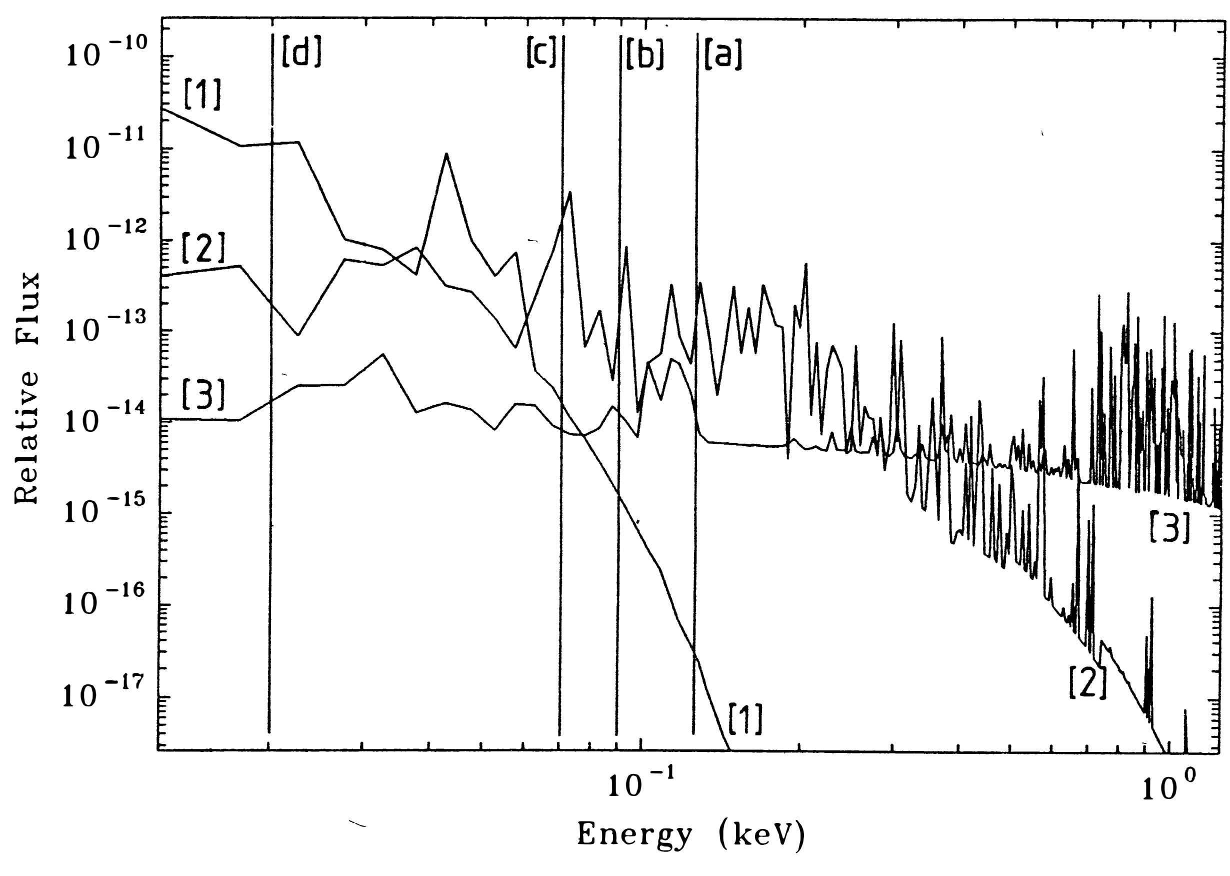
Hot white dwarf stars are sufficiently luminous in the XUV to be potentially observable out to distances approaching several thousand pc. On comparing this figure with the average MFPs of Table 2, it is clear that in practice the effect of the ISM will largely determine the viewing horizon. Taking the approximate temperature limits of figure 4 and the mean horizon allows the total number of WDs that may be detected in each band to be estimated, provided the space density is known. Fleming, Liebert and Green (1986) present a summary of space densities for DA and DO/DB WDs subdivided by temperature.

A total of approximately 1500 WDs is known to exist, of which ≈ 30% (about 450) have temperatures to which the WFC is sensitive. Comparing this figure with the number of WDs that the WFC is expected to see (≈ 2500) shows the statistical value of the survey. Indeed, given that space densities are generally determined from optical identifications this prediction may well be an underestimate.

5. OBSERVING COOL STARS

Pye and McHardy (1987), hereafter P & M, have discussed in some detail the capabilities of the WFC with respect to cool stars, including late type main sequence stars, dMe flare stars and active binary systems (eg. RS CVns). They

Fig. 5. Spectra of an optically thin thermal plasma at three temperatures: [1] 10^5K, [2] 10^6K and [3] 10^7K. Filter bands are marked as in figure 3.



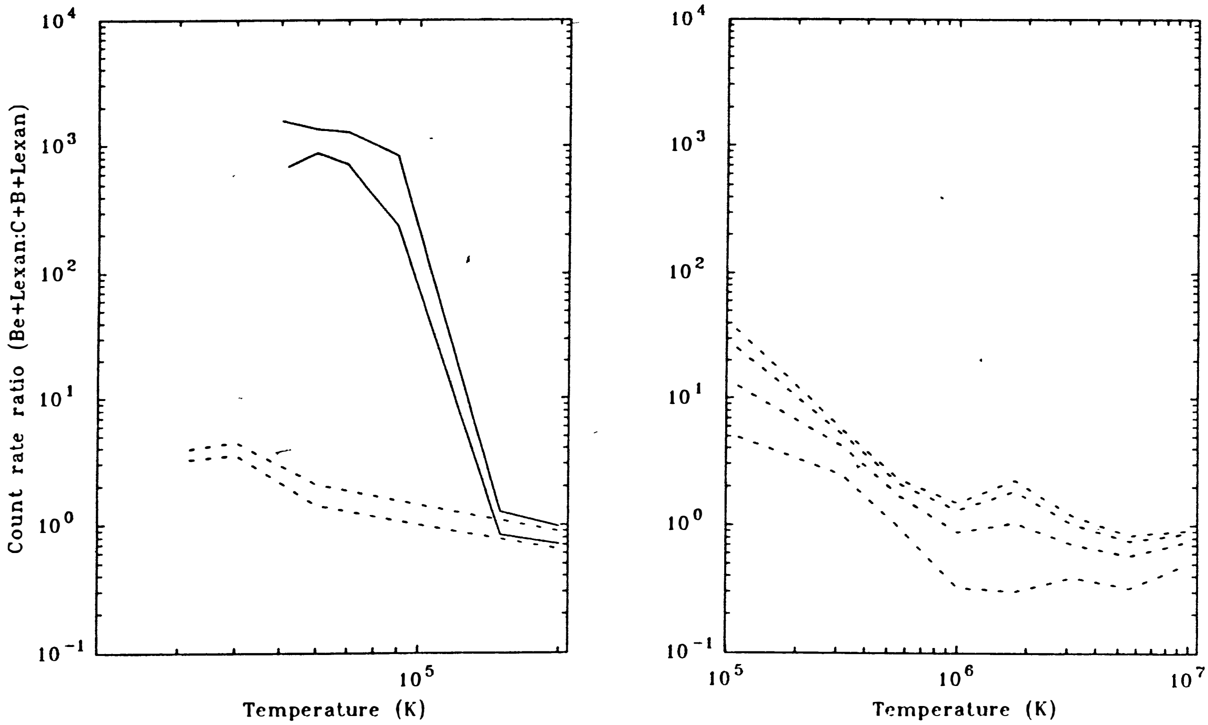


Fig. 6. The ratio of Be+Lexan to C+ B+ Lexan count rate for white dwarfs (left hand panel) and cool stars (right hand panel) as a function of temperature. The white dwarf atmospheres are pure H (dashed lines) and pure He (solid lines) with upper and lower curves representing column densities of 10^{18} and 10^{19} repectively in each case. The column densities for the Raymond and Smith cool star model are 10^{18}, 3×10^{18}, 10^{19} and 3×10^{19} from top to bottom.

vary widely in X-ray luminosity ranging from $\approx 10^{26}$erg s^{-1} up to $\approx 10^{31}$ erg s^{-1} in the most active RS CVns (eg. Rosner *et al*, 1985; Walter *et al*, 1980). Such X-ray emission arises in hot thin plasma lying in the transition regions and coronae of these stars with temperatures lying in the range 10^5 to a few times 10^7K. Figure 5 shows the spectra of a thermal plasma, based on the data of Raymond and Smith (1977), for temperatures in this range. The WFC filter mean energies are indicated showing how plasma of different temperatures will be sampled.

The quiescent XUV luminosity of main sequence stars can be estimated by scaling X-ray luminosities (see P&M), as seen by the EXOSAT mission and assuming a typical solar spectrum. It is expected that these stars will only be detected out to distances $\approx$ 25 pc where the absorbing column is still quite low ($\approx 5 \times 10^{18}$ cm^{-2} on average). Active binaries, such as RS CVns are much more luminous and likely to be observed out to 100pc or more. From known space densities (see P&M), it is expected that the WFC will detect $\approx$ 1000 cool main sequence stars and $\approx$ 10 RS CVn systems. Many cool stars are variable sources, as a result of flaring and rotational modulation of active regions. In binary systems eclipses can also lead to variability and are in fact, a useful diagnostic tool for determining the spatial distribution of coronal plasma, as demonstrated by EXOSAT (eg. White *et al*, 1987). The typical orbital periods of RS CVn systems lie in the range 1 – 14 days. During the survey the viewing axis of ROSAT will scan in ecliptic latitude (θ) at a rate of $\approx$ 4 degree min^{-1} and in longitude (ϕ) at $\approx$ 1 degree day^{-1}. A source will come within the 5 degree WFC field of view for $\approx$ 5/Cosθ days for durations up to $\approx$ 1min every orbit ($\approx$ 1.5hrs). As the minimum coverage of a target is 5 days ($\theta = 0$) it can be seen that the WFC coverage is well matched to monitor RS CVn emission throughout at least a substantial fraction of a binary period.

Cool stars are the major identified class of flaring X-ray source. The repeated observing of individual objects, as described above will lead to some flare detections. P & M have estimated the sensitivity of both the WFC and the ROSAT XRT to events detected in a single pass over a source to be $\approx$ 15μJy (at 100Å) and $\approx$ 0.5μJy (at 1keV) respectively. Convolving these figures with transient event frequencies in previous instruments yields estimates of the number expected in the ROSAT sky survey. They estimate that the XRT will see $\approx$ 180 flares and the WFC $\approx$ 12, ranging in duration from a few seconds to a few hours.

6. THE WFC AS A DIAGNOSTIC TOOL

As well as just detecting sources, the WFC can give us information about them. The survey will be performed in two 'colours' with 2 extra, lower energy bands, available during the pointed phase. For most sources the WFC will provide a count rate measured in one survey filter and either a count rate or upper limit measured in the other. The parameters that we might wish to determine using the data are temperature (T), column density (N_H) and, in the case of WDs, the atmospheric composition to some degree.

The ratio of Be+Lexan and C+B+Lexan count rates (R) are shown, as a function of temperature, in figure 6, for the WD pure H and pure He atmospheres and optically thin thermal plasma. Data are only displayed for temperature components that can be detected in both filters. Except for a narrow temperature range ($\approx 5 \times 10^4 - 10^5$K) of pure He atmospheres, R has no unique value that can determine the object being observed (and these plots do not include other possible types, eg. AGNs). Hence, the survey must be well supported by a programme of identifications. This should be quite easy for cool stars as they are well observed and catalogued but a significant fraction (> 50%) of WDs seen in the survey will have no known optical counterpart.

An example of the problem of interpretation of such data is given by the 1984 EXOSAT observation of the RS CVn HD155555 (Barstow, 1987; figure 7). Using the Raymond and Smith (1977) thin plasma model a curve of T/N_H can be generated where the predicted count rate

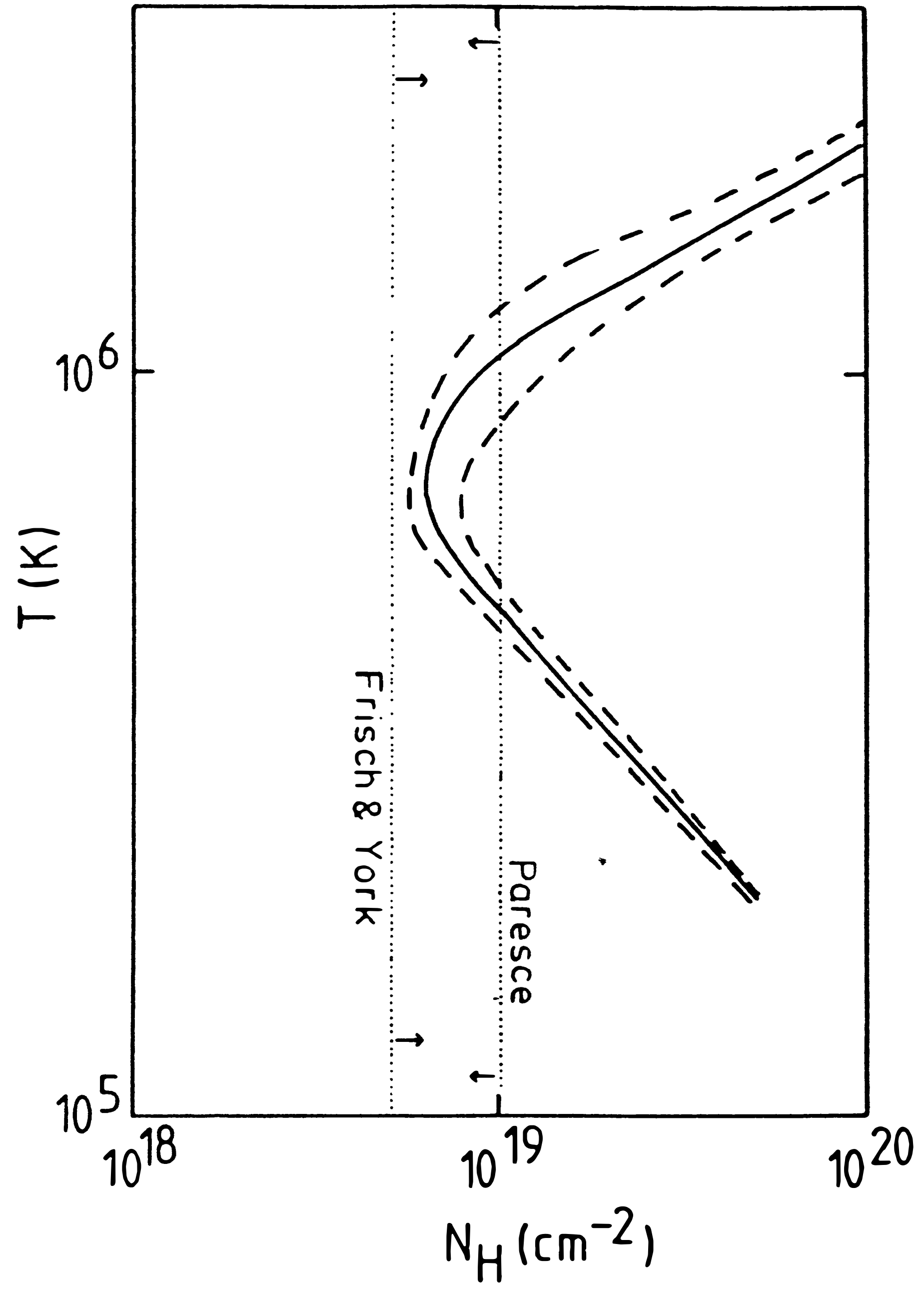


Fig. 7. Plasma temperature (T) as a function of column density (N_H) for the observed mean filter count rate ratio (Lexan:Al/parylene = 2.6) of HD155555. Dashed lines are $\pm 1\sigma$ contours.

ratio (Lexan:Al/parylene) agrees with that observed (2.6). The temperature range can only be further constrained (to $5 \times 10^5 - 1.3 \times 10^6$K) with other information in this case N_H limits from Paresce (1984) and Frisch and York (1983). If some normalisation constant is available for the source model spectrum, such as the optical magnitude for a WD, a unique solution might be determined. This is illustrated in figure 8 where T/N_H curves are displayed for the hot He rich WD K1-16 (Barstow, 1987), corresponding to the observed Lexan and aluminium/parylene count rates (0.019 and 0.0019 cs^{-1} respectively) with a Wesemael pure He model spectrum normalised to $m_v = 15.09$. The curves meet at the point corresponding to 127000K and 1.7×10^{20} cm^{-2}. Note however, that additional data (in this case optical spectra) are needed in order to choose a model atmosphere. Data available from other filters will improve the constraints on T and N_H etc. and also decrease the dependence on supplementary data from other wavebands.

7. CONCLUSION

The WFC will make the first all-sky survey of the XUV energy band. With luck several thousand new sources will be observed of which the majority will be white dwarfs and cool stars. This should greatly expand our understanding of the structure and evolution of these objects. We note that a significant fration (> 1000) will probably be uncatalogued and that a major programme of optical observations will be needed to make the optimum use of the survey data. Furthermore, it is likely that new classes of source, peculiar to the XUV will be discovered.

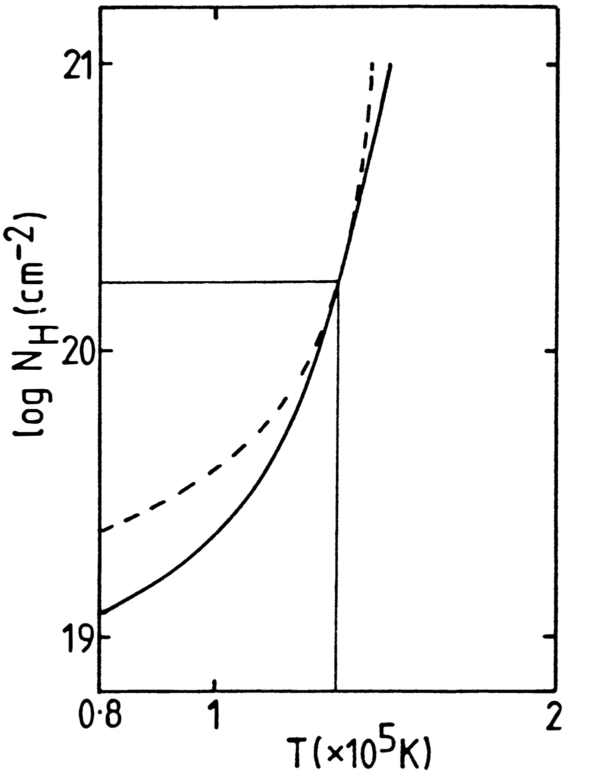


Fig. 8 T/N_H curves of constant count rate for K1-16, corresponding to Lexan (solid line) and Al/parylene (dashed line) filters.

8. ACKNOWEDGEMENTS

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THE QUICK-LOOK FACILITY FOR THE XUV WIDE FIELD CAMERA ON ROSAT

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The British XUV Wide Field Camera (WFC) will form part of the ROSAT X-ray astronomy satellite due to be launched in 1990. Since commanding of the satellite and data reception will take place in Germany, project staff in the UK will not have immediate access to telemetry data and thus will be unable to carry out near real-time monitoring of the functioning of the instrument and the quality of the scientific data returned. This will be the primary responsibility of the WFC Quick-Look Facility (QLF). Attached to the ROSAT Science Data Centre (RSDC) at the Max Planck Institute for Extraterrestrial Physics (MPE) near Munich, the QLF will serve as the front-end of the WFC ground system. The Planned tasks and operation of the QLF and its interface with the UK and German ground systems are outlined.

1. INTRODUCTION

The WFC will carry out the first all-sky astronomical survey in the wavelength band 60 - 200Å. The survey phase of the ROSAT mission is expected to be completed within nine months after launch and will be followed by a 'pointed phase' dedicated to proposed research programmes to which time will be allocated on a competitive basis. The anticipated lifetime of the mission is around 2 to 3 years.

Commanding of the satellite and data reception from both the German and British instruments will be the responsibility of the German Space Operations Centre (GSOC) at Oberpfaffenhofen near Munich. Shortly after each brief contact period, data received at the groundstation will be transmitted over a dedicated data link to the RSDC. The WFC data and WFC-relevant spacecraft housekeeping data will be passed to the WFC 'Quick-Look Facility, so called because its primary purpose is to sample WFC housekeeping and science data shortly after reception in order to monitor the health and functioning of the instrument and facilitate prompt response to anomalies and unexpected events.

Details of the WFC instrument and the overall ground system are presented in accompanying articles in this issue [1,2]. Here the QLF, its functions and planned operation are described.

2. OVERVIEW OF THE QLF AND ITS RESPONSIBILITIES

The hardware facilities at the QLF will consist of a DEC Micro-VAX II computer with disk and tape drives and associated peripheral devices such as printers, VDUs and hardcopy units. The computer will have a DECNET link to the German ROSAT VAX computers at the RSDC and network connection (e.g. EARN/JANET) top the WFC project centres ion the UK. It is foreseen the during nomal mission operations the QLF will be manned by two resident staff and two visiting WFC project astronomers on tours of duty of a few months.

The primary duties of the QLF staff will be to:

1. Analyse WFC and relevant spacecraft housekeeping data and a portion of the science data in order to monitor the performance of the instrument, identify anomalies and assess the progress of the sky-survey.
2. Devise and initiate corrective action in the event of malfunctions, in collaboration with project staff in the UK and Germany.
3. Produce command loads for uplinking.
4. Generate a 'first-cut' sky-survey XUV source catalogue and carry out some scientific data analysis, especially in respect of anomalous or transient sources.
5. Act as the interface between the WFC project in the UK and the ROSAT science and operation centres in Germany.

Requests for survey or pointed observations with the WFC will be received at the QLF from the WFC UK Data Centre (UKDC) at the Rutherford Appleton Laboratory. These, together with requests for calibration and test observations, will be merged at the RSDC with similar requests for observations with the German X-ray Telescope (XRT) (which includes a focal plane instrument provided by the US) and then passed on to operations staff at GSOC. There the information in the observation requests will be used to generate the *Mission Timeline* (MTL). This is the optimised master plan of all intended spacecraft, XRT and WFC operations which will take account of celestial and spacecraft operational constraints in addition to observational priorities. QLF and MPE staff will check the MTL against the original observation requests and, in the pointed phase, ensure that the total observation times allocated to German, UK and US guest observers are in the agreed ratios. The approved MTL then becomes the input for the generation at GSOC of a combined spacecraft, XRT and WFC telecommand timeline. The QLF will be responsible for creating and syntax checking the command blocks for WFC operations. These will consist of commands to be incorporated into the final telecommand timeline which trigger operations directly, and time-tagged (deferred) command sequences which are loaded into the WFC on-board computer and activated by commands in the timeline.

After execution of observations, science and housekeeping data stored on the on-board tape-recorder will

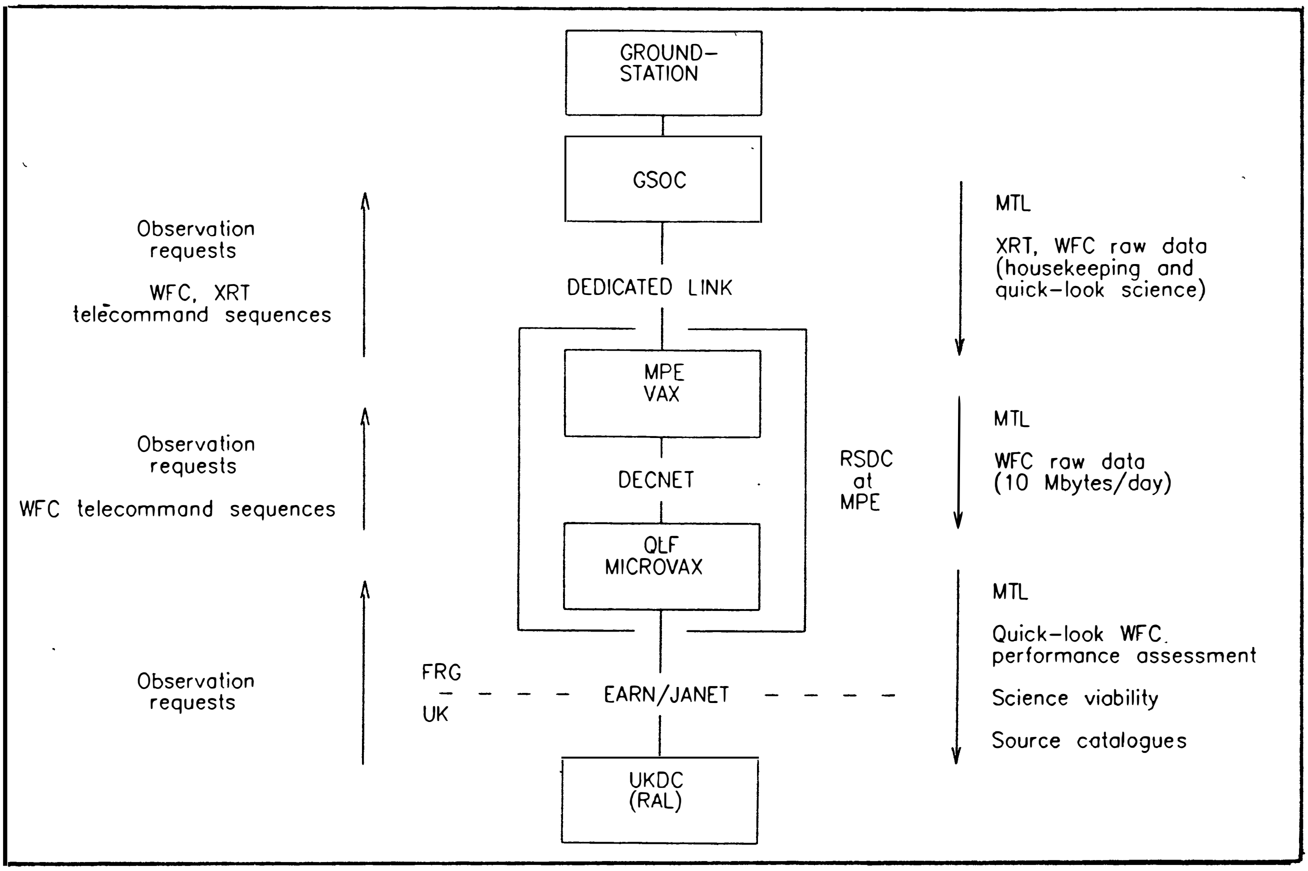

Fig. 1. Primary WFC information and data flow through the QLF, illustrating its role as the link between the British and German ground systems.

be transmitted down to the ground-station during the five or six brief (~8-minute) contact passes per day. During normal operations the WFC housekeeping and calibration data will arrive at the QLF, via the MPE computer, within about 30 minutes after reception. One or two hours after this a portion of WFC science data (about twenty per cent of the daily total, corresponding to three orbits) and relevant spacecraft housekeeping and attitude monitoring data will be received at the QLF. Present planning calls for at least one member of the QLF staff to be on duty during the eight-or-nine-hour contact cycle to check the data as it arrives in order to promptly identify instrument anomalies and unexpected events. A more detailed analysis of WFC housekeeping and 'quick-look' science data will be performed at the QLF shortly afterwards during normal working hours.

The function and interfaces of the QLF in the overall ground system are summarised in Fig.1.

3. DATA PROCESSING

In order to meet the required ~24 hour turnaround time for processing of the daily influx of some 10 Mbytes of raw telemetry data, the QLF will depend heavily on automatic procedures which require little, if any, manual intervention. As a result, and since tape handling and storage facilities at the QLF will be at a minimum, the use of the planned ~600 Mbytes of disk capacity will have to be carefully budgeted. It will be desirable to retain raw data received at the QLF on disk for about one month, thus facilitating any re-processing and re-analysis of the data that may become necessary before the more sophisticated analysis to be performed in the UK is completed.

The scheme for handling downlink data at the QLF is summarised in Fig. 2. The software interface to the MPE VAX computer will be a communications package which accepts raw data via the DECNET link and sorts them into various disk-files according to the data type. The most important aspect of routine analysis at the QLF will be the WFC status and health monitoring. This will be performed by means of a dedicated software package which will operate on housekeeping and science data and generate files containing information on: 1. changes of instrument status with time, 2. the viability (or usefulness) of the science data, based on deviations of instrument housekeeping parameters from nominal values during observations, 3. long-term trends in instrument characteristics, and 4. excursions of housekeeping parameters beyond pre-defined acceptable limits (limit failures). Assessments of long-term variations in instrument performance and summaries of science viability will constitute an important part of the regular feedback of information to the UKDC.

A further requirement is the production of a preliminary 'first-cut' XUV source catalogue from the twenty per cent portion of survey science data received at the QLF. The processing of quick-look survey data will be based on procedures at present under development for use at the UK WFC centres (see [2]). After initial attitude and calibration processing, strip images covering 5 degrees ×360 degrees of sky will be produced, each corresponding to one orbit's worth of data. These images will be searched for point sources using algorithms from a science data analysis library which will be kept on disk at the QLF. In this way daily catalogues of sources can be compiled immediately after reception of the raw telemetry data.

Since the sky coverage of the orbital strip images progresses by 1 degree per day at the ecliptic equator, while the instrument field of view is 5 degrees ×5 degrees, any detectable source will appear on consecutive images for at least five days (as the survey scans will pass through the ecliptic poles, the duration of multiple

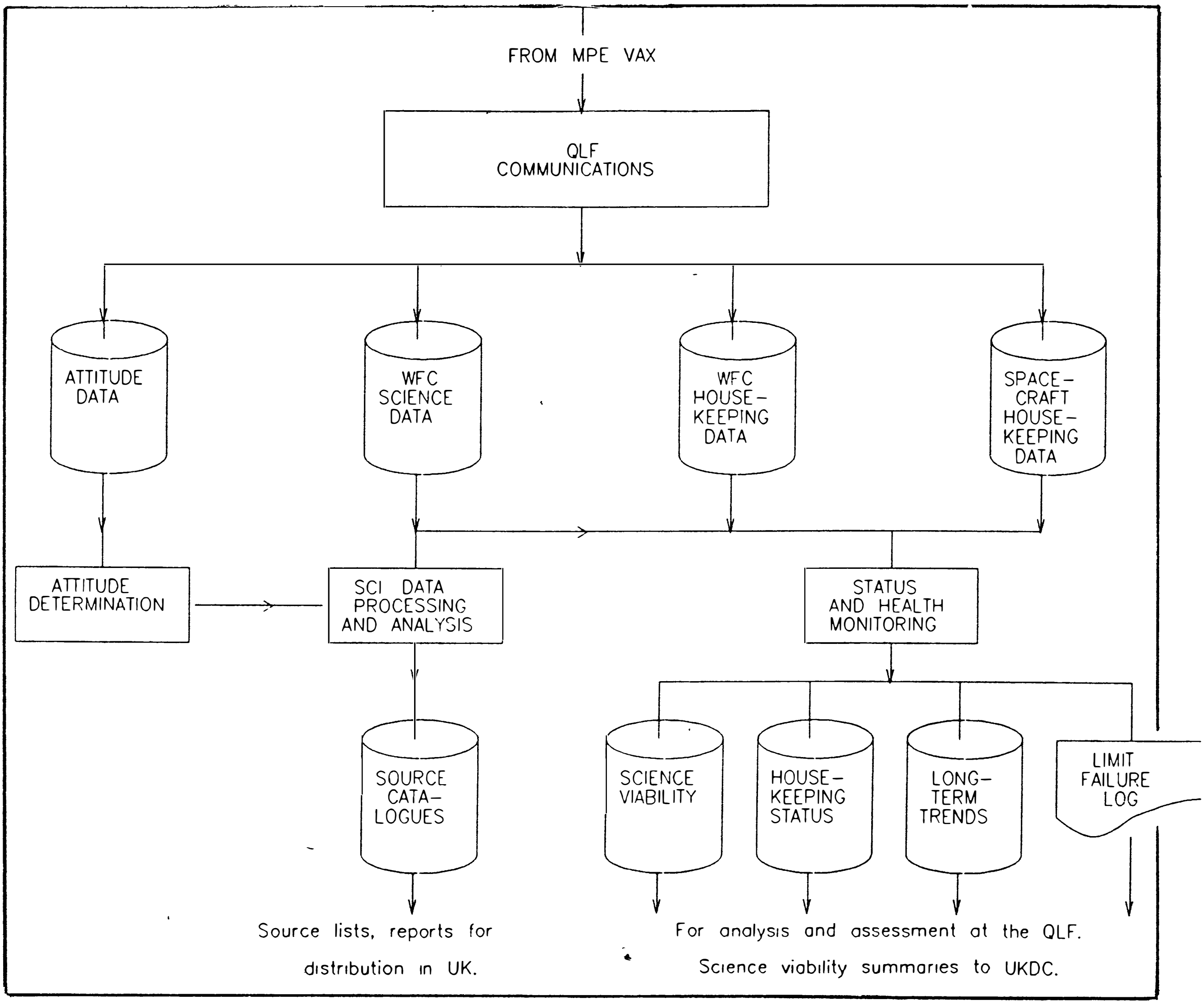

Fig. 2. Downlink data flow at the QLF

coverage will be much longer for sources at high ecliptic latitudes). Therefore transient and variable sources should be identifiable by comparing their appearances on a number of consecutive images.

While it will not be feasible to perform a sophisticated attitude solution at the QLF, the attitude data available from startrackers mounted on both the XRT and WFC instruments should enable the positions of detected point sources to be determined to one arcmin or better. Comparisons of the WFC source data with the positions and projected XUV fluxes of known objects which are candidate XUV sources will enable the scientific performance of the instrument to be monitored in the most fundamental way. In addition, this preliminary quick-look survey has the potential for rapid identification of unexpected or unusual phenomena, e.g. anomalously bright or variable sources, which could be of immediate interest to the wider astronomical community and warrant follow-up observations with other astronomical instruments in different wavebands. These observations could be arranged to be simultaneous with ROSAT coverage on subsequent orbits.

4. DAILY TASKS AT THE QLF

It is presently anticipated that the normal daily work load at the QLF will be managed by a staff complement of four. On any day one of these would be responsible for covering the eight-or-nine-hour ground contact cycle during which there will be brief periods of telemetry exchange with the satellite and raw data will be passed to the QLF. Since the nature of the orbit will cause the ground contact times to advance by about 17 minutes per day, this will very often involve working unsociable hours. Visiting QLF staff would spend about a half of their tours of duty on this important aspect of QLF work. Tours of duty of consecutive visiting duty astronomers will overlap to ensure some continuity of experience apart from that of the two resident staff. Each of the five WFC project centres will provide one or two scientists for manning the QLF

Apart from the main duties of monitoring the operation, health and performance of the WFC, QLF staff will have several additional tasks. These will include overseeing the regular dispatch of 'master data' tapes, containing *all* the raw WFC data, from Germany to the UKDC. These tapes will constitute the primary WFC data return to the UK. It is agreed that during the pointed phase of the mission UK astronomers will be allocated a share of observation time with the German instrument, and *vice versa*. During this phase the QLF will have responsibility for coordinating the exchange of WFC and XRT pointed observation data between the UKDC and Germany.

Finally, while the planned scope of the QLF does not extend to the provision of research facilities for visiting guest observers, it is intended that staff will have the

opportunity to pursue research projects at the QLF. These might include, for example, studies of 'targets of opportunity', transient astronomical phenomena such as novae or supernovae which arise suddenly and unpredictably and may warrant immediate observation by the satellite, with consequent interruption of the scheduled observing programme. In such cases the capacity to carry out some rapid analysis and interpretation of data at the QLF will be most important for ensuring maximum scientific return from the substitute observations with minimum disruption of the scheduled programme.

Acknowledgements

The development of the QLF concept is the result of close collaboration by ROSAT WFC project staff at the five participating institutes: University of Leicester, Rutherford Appleton Laboratory, Mullard Space Science Laboratory, University of Birmingham and Imperial College of Science and Technology. The support and cooperation of our colleagues at MPE, Garching and GSOC, Oberpfaffenhofen are very much appreciated.

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THE EXTREME ULTRAVIOLET EXPLORER MISSION: INSTRUMENTATION AND SCIENCE GOALS

Stuart Bowyer, Roger F. Malina and Herman L. Marshall

NASA's Extreme Ultraviolet Explorer (EUVE) will carry out an all-sky survey from 80 to 800Å in four bandpasses. It is expected that many types of sources will be detected, including white dwarfs and late type stars. A deep survey will also be carried out along the ecliptic which will have a limiting sensitivity a factor of 10 better than the all-sky survey in the bandpass from 80 to 300Å. The payload includes a spectrometer to observe the brighter sources found in the surveys with a spectral resolution of 1 to 2Å.

1. A SHORT HISTORY OF EUV ASTRONOMY

Until 1975, there was very little expectation of significant astronomical benefit to observing the sky in the extreme ultraviolet (EUV,100-1000Å). This pessimism resulted from inadequate knowledge of the opacity of the interstellar medium in the EUV and the expected number of EUV sources; it was also a reflection of the limitations of prior instruments. The first detection of a non-solar EUV source was made with an experiment on the Apollo-Soyuz mission in 1975, described by Bowyer *et al.* (1). Lampton *et al.* (2) reported that a source was found in the constellation of Coma Berenices which turned out to be the hot white dwarf HZ 43. This source is still the brightest known source of EUV radiation.

Several other sources, a binary consisting of a white dwarf and a red dwarf, and a cataclysmic variable, were also shown to be EUV sources in the Apollo-Soyuz experiment. A re-evaluation of the photoelectric absorption of EUV radiation by interstellar hydrogen and helium (3) was combined with better, lower estimates of the average density of the interstellar medium (ISM) (see Paresce *et al.* [4] and references therein), indicating that a survey of the entire celestial sphere should detect sources within 100 parsecs from the sun and possibly farther in some directions. This region contains many potential sources of EUV radiation, so the Extreme Ultraviolet Explorer (EUVE) was proposed to search for these sources and establish a basic catalogue for future work in the field.

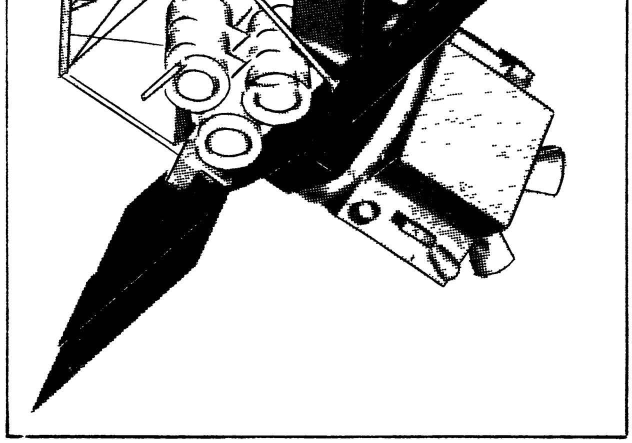
2. THE EXPLORER DESIGN

The detailed design of the EUVE instruments has been described in a number of publications (see Bowyer 1986 [5] for a recent overview). A schematic is shown in Figure 1, which shows EUVE as it would appear as deployed in orbit. Each survey telescope includes a grazing incidence mirror (6) which is focused on a microchannel plate detector (7). The EUV bandpasses are defined by thin plastic or metal filters (8). The detectors are operated in single photon counting mode; sources are discovered only after the satellite's pointing history is combined with the photon positions on the detectors.

The spacecraft is a new reusable version of the Multimission Modular Spacecraft (MMS). It is being built by Fairchild for the Goddard Space Flight Center and relies substantially on previous MMS designs. The result will be called the Explorer Platform and will be dedicated to the Explorer series of scientific satellites. EUVE is currently scheduled for launch in August, 1991, on a Delta rocket. There are no special orbit or launch time constraints, so the satellite will be launched into a standard orbit at about 500 km altitude at a 28 degree inclination to the Earth's equator.

When the MMS was first suggested as the spacecraft for EUVE, it was expected to launch on the Space Shuttle. Following the Challenger disaster, EUVE was redesigned to be compatible with both the Space Shuttle and the Delta. Figure 2 shows how the spacecraft might look within the Delta rocket's payload shroud. After a 30 month mission, consisting of six months of survey work and two years of spectroscopy operations (see below), the science payload will be demated from the Explorer Platform in-orbit by a Space Shuttle crew using the remote manipulator arm, and it will be replaced by the next experi-

Fig. 1. Schematic of EUVE after deployment. The solar panels are attached to the Payload Equipment Deck, which is mounted to the Multimission Modular Spacecraft. Three scanning telescopes are stacked on the PED, and the Deep Survey/Spectrometer telescope is oriented along the spacecraft spin axis, the axis of most symmetry



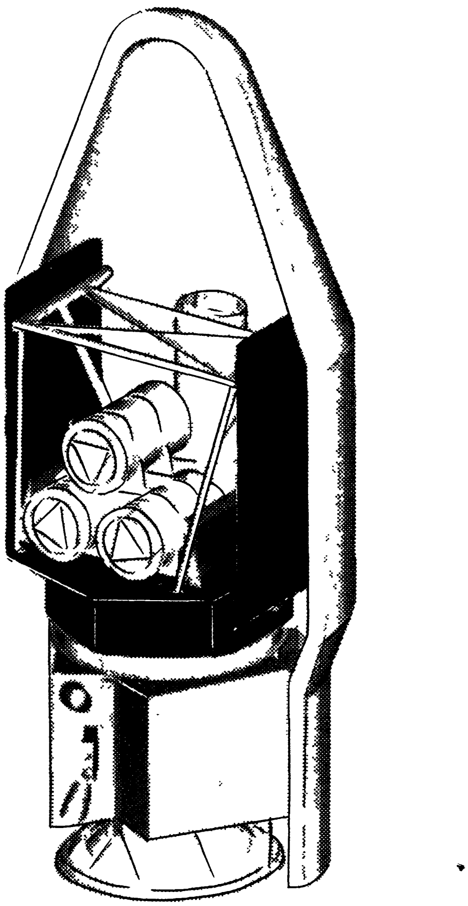


Fig. 2. EUVE in the Delta launch configuration. Note that the solar panels are folded up along the science payload and the telescope doors are closed.

ment in the Explorer series: the X-ray Timing Explorer (XTE).

The all-sky survey is carried out using three similar "scanning" telescopes which scan along great circles in the sky. As the Earth travels about the sun, these overlapping great circles eventually cover the entire sky. The deep survey and spectrometer functions are accomplished using a single "deep survey/spectrometer" telescope which is oriented along the spin axis of the spacecraft (see Figure 1). During the all-sky survey, this telescope concentrates on a small region opposite the Sun, in the direction of the Earth's shadow. The background that interferes most with EUV observing – due to radiation from particles trapped in the Earth's magnetosphere – is minimised in this direction. The reduced background and increased exposure time result in significantly increased sensitivity. The effective exposure times will be 2000 sec in the all-sky survey with the two Type I scanners, 700 sec with the Type II scanner (see below) and 17,000 sec in the deep survey.

Table 1

Filter	Telescope	Median wavelength (Å)	Wavelength range (Å)	MDF (μJy)
Lexan/B	Scan. I	120	60-195	2.3
Al/C	Scan. I	215	160-285	110
Al/Ti/Sb	Scan. II	495	400-600	400
Sn	Scan. II	620	520-750	1400
Lexan/B	DS	120	70-190	1.0
Al/C	DS	270	160-420	9

The scanner instruments have a field of view of five degrees diameter, while the deep survey instrument has a 2.0 degree field of view. The image quality varies from 10 arc seconds on axis to more than five arc minutes (radius) at the edge of the field of view due entirely to the fact that the detector surfaces are flat and the focal surface for the mirrors is curved.

In Table 1 we show the bandpasses defined by the filters for the scanners. These filters are still in development and may be different from the ones actually used. The effective area of the bandpass accounts for the mirror geometric area, the mirror reflectivity, the filter transmission and the detector quantum efficiency. The wavelength range is given by the ten per cent effective area points. The sensitivities of the scanner and deep survey instruments are also summarised in Table 1, which shows the minimum detectable flux (MDF) in each bandpass. The MDF is calculated assuming a flat photon spectrum and a five sigma detection of the source above background, where the background is calculated as the sum of the detector internal background and the diffuse sky background. The latter source of background generally dominates.

Because the spectrum of many EUV sources is expected to rise in the UV or soft X-ray, the measurement of the instrument throughput outside the filter bandpasses will be an important goal of the calibration to be carried out before launch. Current models for the filter bandpasses indicate that B stars brighter than 5th magnitude (roughly 100 in the sky) will be detected in some of the filters. Similar analysis will be performed to evaluate the sensitivity of the instruments to known soft X-ray sources, with a goal of keeping the number of sources detected only shortward of 80Å to a minimum. In some areas we expect that the flight instruments will have better performance than currently modelled. These may lead to increases of sensitivity of up to a factor of 2 over those shown in Table 1.

In the course of EUVE development and prototyping, several technological advances in space physics instrumentation have been made by the Space Astrophysics Group that have significantly improved the potential return from the EUVE mission. For example, it was found that potassium bromide would make an excellent photocathode coating for the Type II scanner and the long wavelength spectrometer channels (9). During the study of filter materials exposed to the residual atmosphere present in low earth orbit, it was determined that a thin coating of boron would protect the (organic) Lexan filter from oxidizing. Finally, a second scanner Type was designed with higher graze angles because of the difficulty encountered designing filters for detectors that detect X-rays as easily as EUV light. The new mirror design (10) is optimised for blocking wavelengths below 200Å while being constrained to the same entrance aperture diameter and focal length. The scanner is of Wolter-Schwarzschild Type II design and is designated the Type II scanner. The geometric area is 390 cm^2, compared to 140 cm^2 for the Type I scanner.

The EUVE payload also includes a three-channel spectrometer covering the 80 to 750Å range with a spectral resolution of approximately 1Å. With this instrument it will be possible to observe the brightest sources discovered in the surveys. A unique, new spectrometer design (11) was invented to take advantage of novel, variable line density gratings which allow high throughput while correcting for the aberrations in the system; this allows good spectral resolution without the use of multiple optical elements. The design has three gratings (for three separate spectral channels) in the converging beam, each picking off one sixth of the mirror's light. The remaining half goes to the direct imaging "deep survey"

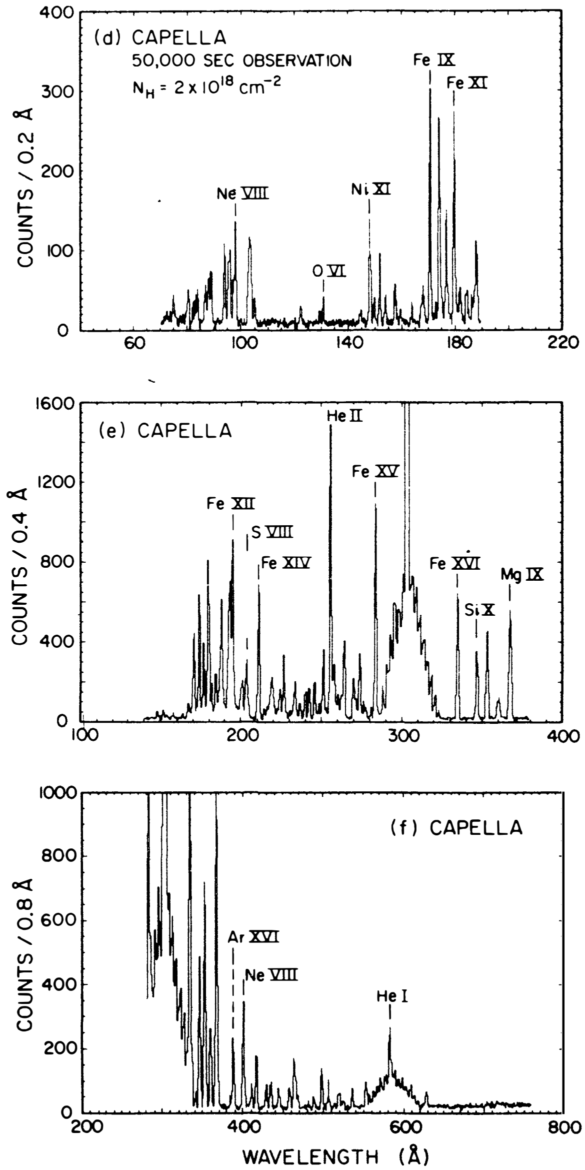


Fig. 3. Simulated spectrum of the coronal source Capella The exposure is 40,000 sec and nominal emission lines based on the solar spectrum are included. Note the richness of the spectrum and that, even at this resolution, there are many blended lines.

detector. Two of the channels employ collimators to reduce the background. The spectroscopy programme will be run entirely as a Guest Observer Programme. A central data analysis facility will be set up at the Space Sciences Laboratory for Guest Observers that will allow users to log in remotely or access data over public networks (12).

The software system is unique in that it was designed to be developed in stages as the hardware is developed. The End-to-End System (EES) contain a complete model of the scientific instruments (13) including optics and electronics, simulates data for input using catalogues of known or potential sources, performs engineering checks of the instrument data, and, finally, executes the data analysis procedures, including source detection, measurement and cataloguing. The EES was used to study the shapes of point source images for examining detection methods (14). It is currently being prepared for its fourth release (of nine) and is being used to aid in the design of spectrometer baffles.

3. SCIENTIFIC PROGRAMME

The primary science data products from the mission will be the all-sky and deep surveys, and the associated catalogues of detected sources. It is anticipated that a number of classes of sources will be observed. From the current (albeit small) catalogue of known EUV sources, it is known that hot white dwarfs will be an important class of sources observed.

The sensitivity of EUVE instruments is such that DA white dwarfs with temperatures of ~70,000 K can be detected at distances of up to a kpc (15). The all-sky survey should yield a substantial number of DA white dwarfs hotter than 25,000 K, allowing a very accurate determination of the luminosity function. An EUV detection can be combined with results of model atmospheres and optical or far UV observations to determine the effective temperature, the He/H ratio in the interstellar medium (or in the white dwarf itself), and the intervening neutral hydrogen column. It may be possible to map the distribution of neutral hydrogen in the solar neighbourhood out to several hundred parsecs with a large sample of white dwarfs.

A speculative estimate of the number of detectable EUV sources was recently made by Pye (16). Using data for a handful of individual objects detected at both EUV and X-ray wavelengths, he estimated that several hundred late type stars will be detectable at a few μJy at 100Å. Most will be of type M, whose temperatures are 3000 K. The emission is thought to derive from the hot corona of the star, which is much more active than that of our sun relative to the total luminosity. The detected sources should be relatively nearby, within ~20 parsecs, so that detections may be expected at longer wavelengths. Very little is known about the corona of stars other than our sun at these wavelengths, so it is very difficult to make estimates of the numbers of potentially detectable sources.

Recent UV and X-ray measurements of bright quasars show that there may be a strong, broad feature in the EUV (17). Such a feature would carry the bulk of the quasar luminosity and may be detectable with EUVE. This light may be due to an accretion disk that feeds the central object, which may well be an extremely massive black hole. The neutral hydrogen in our galaxy severely limits our ability to detect quasars. They are unlikely to be detectable at 200Å but may well be observable at 100Å.

We have also investigated the possibility of detecting neutron stars on the basis of their thermal emission. Nomoto and Tsuruta (18) estimated that the stars would have a luminosity about one tenth that of the sun, which, given that the spectrum is that of a black body, implies a temperature of 6×10^5 K. The peak of the spectrum occurs at 60Å, which produces substantial emission in the EUVE Lexan/C band. Considering the sensitivity of the instrument in that band during the survey and accounting for absorption due to the interstellar medium, we find that such neutron stars may be detectable out to about 100 pc. The average distance to a neutron star of this luminosity can be determined roughly from the age, ~ 3×10^7yr., the average formation rate, ~ 1 per 50yr, and the volume of the Galactic disk, ~ 150 kpc^3, giving 70 pc. Thus the expected number of neutron stars in the EUVE survey is about 3, but could be more in directions of low interstellar column density. It is also possible that "defunct" pulsars accreting material from the interstellar medium will show up in the all-sky survey. It has been estimated that perhaps 10 pulsars with appropriate characteristics reside within 20 pc of the Sun, and could be detectable.

Other classes of sources that are expected to be detected include flaring stars, and various types of cata-

MEASUREMENT OF INTERSTELLAR HELIUM TO HYDROGEN RATIO

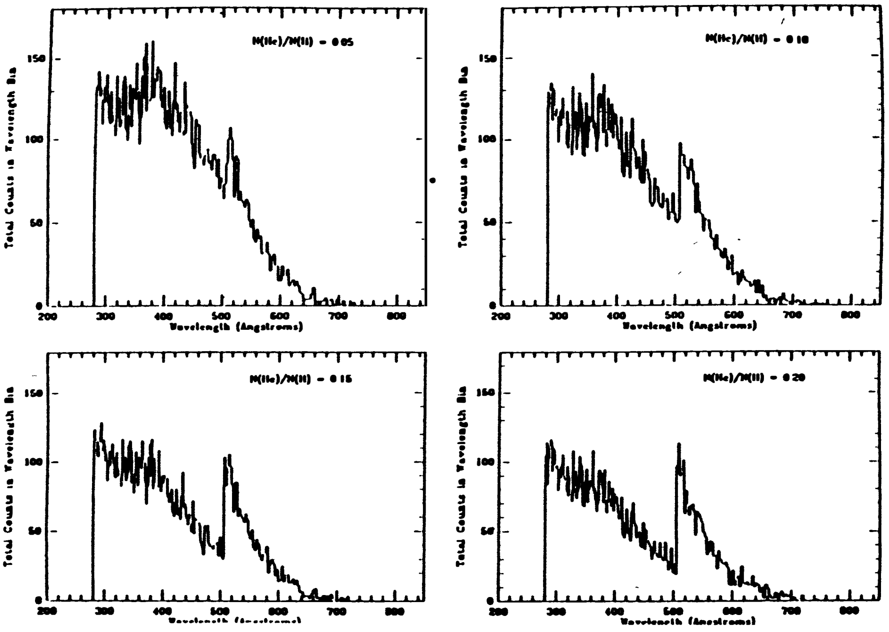


Fig.4. Simulation of data from a source with an intensity of 0.05 of HZ 43. The intervening hydrogen column density is 10^{18} cm ^{2} and the helium to hydrogen ratios are shown Only data from the third channel are shown.

clysmic variables such as dwarf novae. It is also known that the moon, Jupiter and Saturn will be observable. If any cometary encounters occur during the mission, observation of the resonant line emission will be possible. Geophysical studies will also be attempted. Not only will EUVE provide useful data on the geocoronal background, it will also be possible to view EUV emission while pointing at the Earth.

Since all the instruments have imaging capability, it will be possible to make observations of extended diffuse objects smaller than the field of view (e.g. EUV emission from the moon due to reflected sunlight, auroral arcs, etc.). Of course as in all explorations of new wavelength bands, it is hoped that new classes of sources not identified at other wavelengths will be discovered.

4. SPECTROSCOPY

The spectrometer will be particularly important when it comes to diagnostics of the coronae of late type stars. It is well known that stars like our sun and cooler have hot coronae that are detectable with imaging X-ray satellites (19). A simulation of the spectrum of the star Capella is an example of this class of source, shown in Figure 3. The range of temperatures that is present in these coronae is under some debate, however. Fortunately, many species of elements common in stellar atmospheres (notably He, C, O, Ne, Mg, and Fe) have strong transition in the EUV. The effective temperatures can range from $\sim 2 \times 10^4$ to $\sim 3 \times 10^7$ K.

Using the detectable white dwarfs as a backlight, it will be possible to measure the ratio of helium to hydrogen in the interstellar medium in order to probe the ionization conditions. Simulations are shown in Figure 4 for various values of this ratio. Background is negligible and only the long wavelength channel is plotted. Thus the spectrometer could be used to detect an abundance of a part in 20 due to neutral helium.

5. ACKNOWLEDGEMENTS

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IRAS POST-MISSION ANALYSIS AT IPAC

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The Infrared Processing and Analysis Center (IPAC) was established at JPL/Caltech in late 1984 after the primary IRAS data products were released. IPAC's charter is to maximise the science return from the IRAS data. This is done by supporting the astronomical community in its analysis of the IRAS data, by reprocessing the IRAS data to generate significantly improved data products, and by actively pursuing numerous scientific investigations. The IRAS satellite may be dead, but the IRAS data continue to live.

1. INTRODUCTION

The Infrared Processing and Analysis Center (IPAC) was established by NASA in 1984 as a cooperative effort of the Jet Propulsion Laboratory (JPL) and the California Institute of Technology to extract the maximum science return from data acquired by the Infrared Astronomical Satellite (IRAS). IPAC accomplishes this purpose by supporting the research of members of the astronomical community and by developing new data products and analysis tools to enhance the utility of the IRAS data. To ensure that IPAC is able to provide state of the art analysis capabilities, members of the IPAC staff perform research using the IRAS data.

The international IRAS mission to survey the sky at infrared wavelengths was conducted from January through November of 1983 [1]. The IRAS satellite and operations have previously been described in this journal [2]. Up to date reviews of the science results from IRAS are given elsewhere [3,4]. The details on the IRAS mission and the primary data products are given in the IRAS Explanatory Supplement [5].

The full IRAS database – including raw data from the mission, intermediate products, and all the IRAS final products – exists in all three of the partner counties. In the Netherlands, the data are archived at the Space Research Department at the University of Groningen and Sterrewacht Huygens Laboratorium at the University of Leiden. In the United Kingdom, the archive centre is the IRAS Post Mission Analysis Facility (IPMAF), Rutherford Appleton Laboratory. In the United States, IPAC is the repository of the IRAS database.

Due to the tremendous success of the IRAS mission, the large data volume generated by the mission, and the continuing scientific potential of the IRAS data, it became clear during the initial processing of the data that it was extremely important to continue to analyse and process the IRAS data. Since JPL had been largely responsible for producing the final IRAS data products, a team of scientists, engineers, and operations staff with intimate knowledge about IRAS already existed. It thus was logical that NASA decided to regroup the IRAS project team at JPL into the IPAC to perform the continuing work. We moved five miles from JPL to new quarters on Caltech's campus, symbolising the shift from the space flight project environment at JPL to the research environment of the university.

In this article we summarise some of the work that has been done at IPAC over the last three years. Section 2 discusses the scientific products, both those that are already in general use and those that are now in development. Section 3 discusses the General Investigator programme, including the processing we offer to visiting scientists and the database that supports that processing as well as improvements to that datebase. Section 4 discusses our plans for products that we envisage as the final round of refinement of the IRAS data.

2. IRAS SCIENTIFIC PRODUCT SUMMARY

The legacy of IRAS resides in the released data products which make it possible for non-IRAS astronomers to easily access and use the IRAS data without having to know many details about the IRAS hardware. One of the major successes of IRAS was the relative rapidity with which the several initial data products were produced and released. Only one year after the satellite ceased operations, the Point Source Catalogue of 245,839 sources, an accompanying Atlas of Low-Resolution Spectra for 5,425 of those sources, a Zodiacal History File of the data from all IRAS survey scans at half degree resolution, and the Sky Brightness Images covering nearly the entire sky with 2′ pixels, all on computer-readable tapes, were released. Literally hundreds of research groups around the world obtained copies of these products essentially free of charge from either the Astronomical Data Center in Greenbelt, Maryland, the U.S. distribution centre, or from the other IRAS centres mentioned above. Within a year, the number of published papers using IRAS increased to a level of about two hundred refereed papers per year.

Other IRAS data products were delayed in order to ensure that the four products mentioned above were released in a timely manner. Also, it was inevitable that corrections would need to be made to the initial set of products, as more was learned about the IRAS data. Thus, the first data released by IPAC were products that had been in progress during the original processing, as well as improved versions of the previously released products. These products are described in Section 2.1 below.

As part of the charter establishing IPAC, we planned to produce two major new products. First, we knew that the IRAS data could be coadded in regions of low source density to achieve a sensitivity three times fainter than the Point Source Catalogue. This product is described in Sec-

tion 2.2 below. Second, because the beauty and utility of the Sky Brightness Images surprised and astounded even us, we planned to reprocess them to significantly improve their scientific usefulness. Specifically, we needed to remove the foreground Zodiacal Emission in order to determine the brightness of the infrared sky beyond the Solar System. After doing so, we could then coadd the three separate images that IRAS made of the sky. As a result of several improvements we expect to achieve a sensitivity six times better than any of these separate images. This product is described in Section 2.3 below.

Finally, the IRAS user community impressed upon us that much was to be gained by efforts to achieve diffraction limited imaging for brighter sources. Thus we began a project, collaborating with four General Investigator groups, to develop software that would accomplish that goal. This effort is described in Section 2.4 below.

2.1 Existing Products

Table 1 lists the major IRAS products that have been published since the initial release of the IRAS catalogue and images in November 1984. The galaxy catalogue, the additional versions of the Sky Brightness Images, and the Small Scale Structure Catalogue were products originally planned to be released along with the four initial data products, but which had to be delayed in order to release the initial products on time. The Additional Observations, as proprietary data for the IRAS Science Team, were released when the proprietary period expired in November 1985 . The other products were the result of our continuing involvement and analysis of the IRAS data.

The *Catalogued Galaxies and Quasars Observed in the IRAS Survey* is a subset of the IRAS point source data pertaining to previously known galaxies and quasars. It was intended as a readily accessible compilation of IRAS data for objects appearing in the most widely used extragalactic catalogues. It is an exception to the general rule that all IRAS products are available in computer readable form, since this was intended to serve as an easily accessible printed volume. Due to public demand, however, we are presently producing version 2 of this product which will be available on magnetic tape. Version 2 of this catalogue will contain version two fluxes from the Point Source Catalogue and fluxes from the Small Scale Structure Catalogue.

Only the Sky Brightness Images for HCON 3 were released with the original data products. (An HCON is an IRAS unit of sky coverage, short for hours-confirming coverage and consisting of a sequence of scans of the sky usually taken on consecutive orbits, about two hours apart. During the first six months, IRAS covered the sky with two HCON units. For 72 per cent of the sky, IRAS completed a third HCON coverage before the liquid helium ran out.) HCON's 1 and 2 were produced by IPAC as part of its post-mission processing. Significant improvements to the stability of the photometric baseline calibration were made during this processing so that we reprocessed HCON 3 and released version 2 of it during this period.

Table 1. Major IPAC Produced IRAS Data Products.

Catalogued Galaxies and Quasars [6]	February 1985
Sky Brightness Images (HCONs 1 and 2)	August 1985-June 1986
Additional Observations [7]	November 1985
Small Scale Structure Catalogue [8]	December 1985
Zodiacal History file (Version 2)	May 1986
Asteroid and Comet Survey [9]	October 1986
Point Source Catalogue (Version 2)	November 1986
Serendipitous Survey Catalogue [10]	December 1986
Catalogue of Large Galaxies [11]	January 1988

The 13,853 Additional Observations covered about three per cent of the sky with a sensitivity of 3-5 times the sensitivity of the survey data that were used for all other data products. These observations for the most part were targeted at previously known objects. The data were released as images with pixel sizes down to 0.25′ with each observation covering typically 1 square degree. There was considerable redundancy in the coverage, including the requirement that every field was observed at least twice in order to be able to remove spurious sources.

The Serendipitous Survey Catalogue of 43,866 sources was the result of processing the Additional Observations in order to produce a catalogue of all point sources that were confirmed between the redundant coverages of each field. Many more sources were observed than just the targets of observation. This catalogue was done in collaboration with S. Kleinmann at University of Massachusetts; R. Cutri, E. Young and F. Low at University of Arizona; and F. Gillett at NOAO.

The Small Scale Structure Catalogue contains 16,740 sources that were resolved by IRAS. These sources are larger than point sources, about 1′, and an upper limit of ~8′ was imposed on sources for this catalogue. These objects are mostly non-stellar sources within our Galaxy, but some are nearby galaxies that are larger than 1′.

The Zodiacal Observation History File (ZOHF) gives total sky brightness in half degree square bins for the whole mission. This file compactly represents the entire scan history of the IRAS satellite and is primarily used to understand the zodiacal emission from our Solar System. As we have continued to refine our understanding of the calibration of the IRAS data (and to correct an embarrassing 0.50 degrees uniform erroneous shift in positions in the original version!) we released a new version of ZOHF.

The Asteroid and Comet Survey gives the IRAS results for 1811 previously known asteroids and 25 comets, including the comets discovered by IRAS during the mission at the Quick-Look facility at R.A.L. [11]. The infrared observations allow albedos and diameters to be calculated for the vast majority of asteroids for the first time.

The Point Source Catalogue as originally released suffered from a systematic error in overestimating fluxes of the faintest sources in the catalogue. The software used to produce the catalogue was designed to process only detections above the three sigma noise threshold and demanded that catalogue sources be seen on a minimum of 2 HCONs. Because some parts of the sky were scanned many times, noise boosted some intrinsically weaker sources above that threshold on a subset of those scans. By averaging only those detections above the threshold, fluxes were overestimated for the weaker sources. Along with statistically correcting these fluxes, we made numerous small corrections and produced version 2 of the Point Source Catalogue.

Finally, W. Rice and collaborators at IPAC did justice to the IRAS data on nearby resolved galaxies by producing the Catalogue of IRAS Observations of Large Optical Galaxies [12]. The survey data were coadded at high resolution for galaxies not observed in the Additional Observation mode and contour maps, brightness profiles and total fluxes of 85 Reference Catalogue galaxies with blue diameters >8′ were produced.

2.2 The Faint Source Survey

The original IRAS data processing for the Point Source Catalogue (PSC) was done by detecting sources in individual detector data streams, and then applying a series of stringent confirmation criteria (seconds, hours, weeks confirmations) to establish the reliability and validity of the sources. Although, by design, this approach led to an

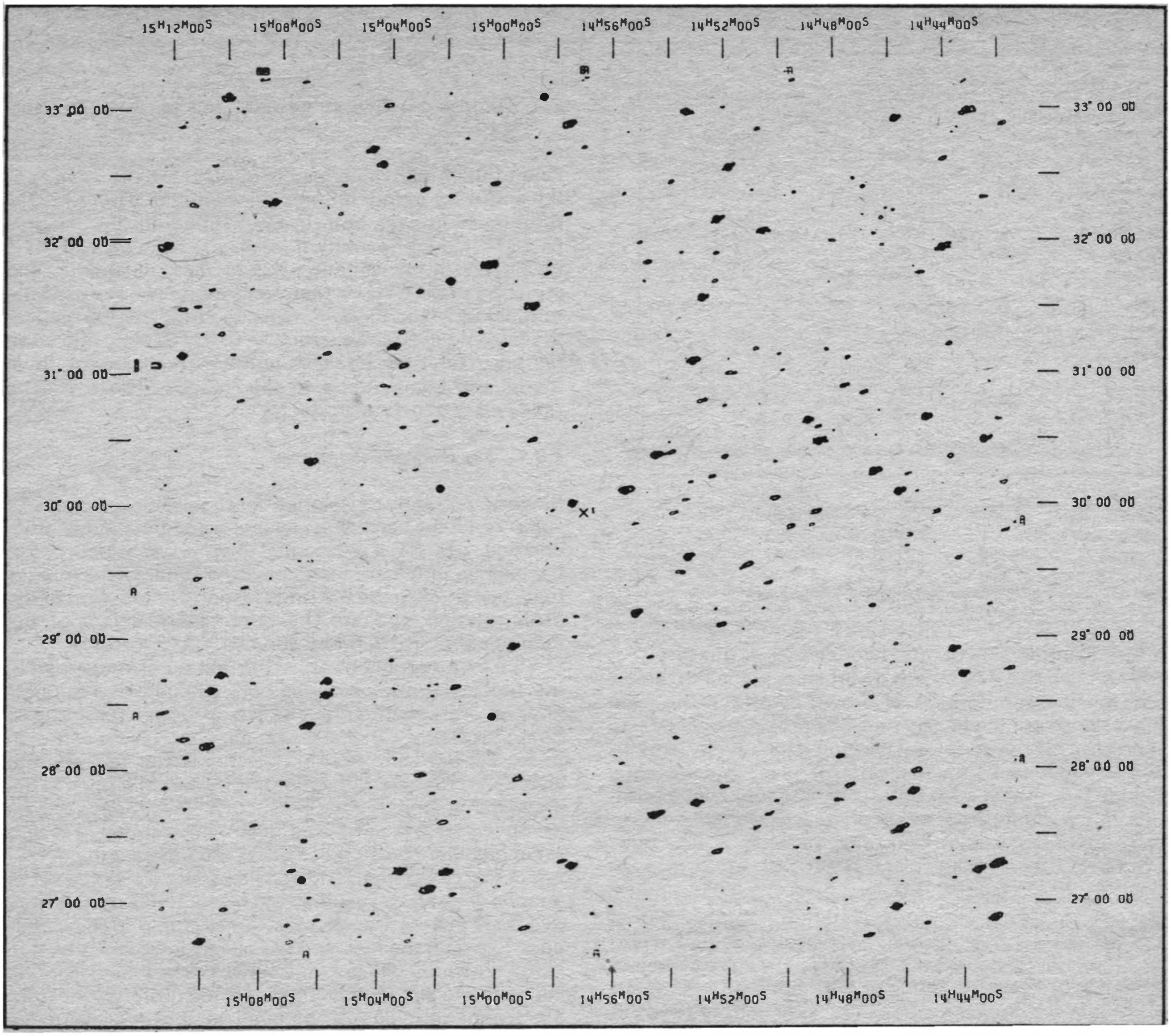


Fig.1. The contour map shows a 6 degree x 6 degree field at high Galactic latitude from the Faint Source Survey; sources brighter than 4σ are indicated. Only 58 of the 1650 valid sources in this field appeared in the Point Source Catalogue supplied by M. Moshir.

extremely reliable catalogue, the full sensitivity possible with the IRAS data was not achieved. Over the course of the IRAS mission each resolution element in the sky was covered typically between eight and twelve independent times. By coadding all the independent sightings and then applying source detection algorithms, it is possible to gain a factor of 2.5 - 3.5 in sensitivity over the original Point Source Catalogue.

The Faint Source Survey (FSS), currently in production at IPAC, is designed to give the most sensitive survey possible for point sources over nearly the entire sky. The only areas actually scanned by IRAS that will be excluded from the survey are locations such as the Galactic Plane where the satellite was limited by source confusion. There are three main products associated with the FSS; the coadded data in the form of images, a database consisting of all potential point sources brighter than three times the local noise, and a Faint Source Catalogue (FSC) of objects chosen such that the catalogue is more than 95 per cent reliable.

The FSC will represent a significant improvement in sensitivity over the PSC. Table 2a compares the characteristics of the FSC and the PSC while Table 2b gives the predicted numbers of different types of sources in the FSC along with the estimated numbers in the PSC. Another comparison between the FSS and the PSC is shown in Figure 1, where the FSS sources with local signal to noise ≥4 are plotted for one 6 ×6 square degree field at high Galactic latitude. Only the brightest 58 of the 160 valid sources in this field appear in the PSC. It is expected that the FSC will contain ~ 170,000 totally new IRAS sources, including over 50,000 new galaxies, hundreds of quasars, and possibly brown dwarfs or new types of sources.

The FSS will result in additional measurements for most of the 120,000 sources that were detected at only a single wavelength in the original catalogue; detection in a second band will yield a single IRAS colour that helps enormously in classifying sources. Two examples that reveal the potential of the FSS are searches for ultraluminous extragalactic sources and for brown dwarfs. The highest redshift determined for an IRAS extragalactic object is $z{\sim}0.44$. The enhanced sensitivity of the FSC will permit the detection of such objects at redshifts $z{>}0.75$. The FSC will, thus, survey five times the volume searched by the PSC making it possible to compare the density of "infrared loud" quasars with that of "UV loud" quasars such as those found in the Schmidt-Green survey. Current evidence suggests that the "infrared loud" quasars are at least as populous as the classical "UV loud" quasars; the coadded survey will permit a

Table 2. Comparison of Point and Faint Source Catalogues.

a Characteristics of Catalogue

CHARACTERISTIC	PSC	FSC
Sky Coverage	96%	70-90%
Relative Sensitivity	1	3
Number of sources	250,000	265,000
Reliability	>.998	>.95
Completeness limits		
12 μm	0.4 Jy	0.16 Jy
25 μm	0.5 Jy	0.20 Jy
60 μm	0.6 Jy	0.24 Jy
100 μm	1.5 Jy	0.8 Jy
One sigma errors for source at completeness limit		
Position		
12 μm	3" × 20"	7" × 41"
100 μm	10" × 22"	29" × 46"
Photometry	10%	20%

b. Predicated Number of FSS Sources in Catalogue for | b | > 10 degrees

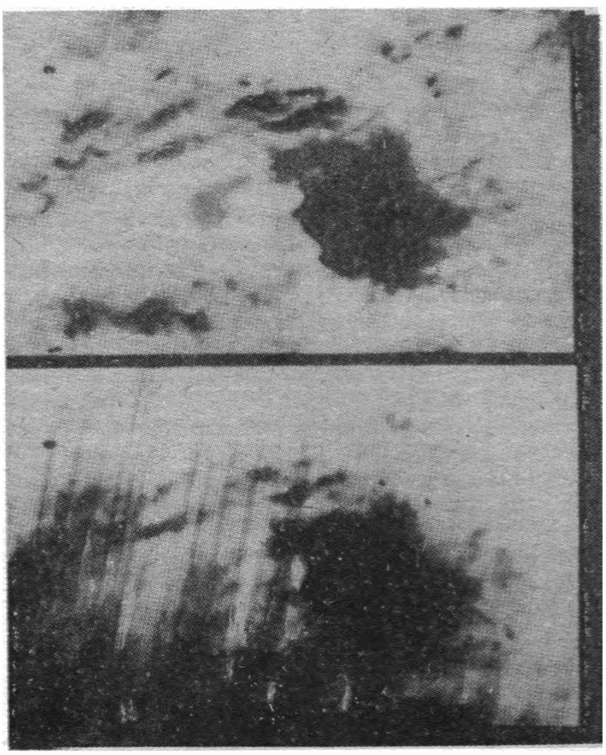
SOURCE TYPE	*PSC*	*FSC*	*NEW IN FSC*
Stars	*54,000*	*125,000*	*71,000*
Extragalactic	*19,000*	*75,000*	*56,000*
Galactic	*16,000*	*63,000*	*47,000*
Cirrus	*21,000*	*?*	*?*
TOTAL	*110,000*	*> 263,000*	*> 174,000*

direct comparison of the two classes of quasars.

The failure to find brown dwarf stars in the PSC sets a limit on the contribution of brown dwarfs to the local mass density of the galaxy that is approximately equal to two times the possible local missing (Oort) mass. The FSS will either detect brown dwarfs or place a sufficiently stringent limit that such objects can be ruled out as contributing a significant fraction of the local missing mass.

The FSS is currently in production at IPAC. The plate production for the high galactic latitude sky, | b |> 50 degrees, was finished in January, 1988 and these images,

Fig. 2 Two views of the Pleiades at 60 μm. Both have similar contrast Fig. 2a is HCON 1; note the in-scan striping and the zodiacal gradient. Fig. 2b is a product of the survey coadd routine BIGMAP which coadded all three HCONs with simple field flattening and stripe removal. Figure supplied by J. Good and G. Laughlin.



along with the corresponding FSC will be released in the middle of 1988. The rest of the survey will be released over the next year.

2.3 Improved Sky Brightness Images and Zodiacal History File

One of the remarkable results of IRAS are the images of the entire sky at four infrared wavelengths. The IRAS Sky Brightness Images both in low resolution (0.5 degree pixels) and high resolution (2' pixels) have proved to be invaluable in investigating the zodiacal dust cloud and structure of the Galaxy. Many astronomers have used the original Sky Flux digital images to study star formation, the infrared cirrus, the structure of the Galaxy, and comets and cometary trails. A number of major improvements are being made to the images. These will be reflected in two data products.

2.3.1 Sky Brightness Images

Since no currently envisioned space missions will make a survey with the sensitivity, spatial resolution and angular coverage of IRAS, it is essential to produce the best possible images of the sky using the IRAS data. These images may well prove to be the most lasting contribution of the IRAS mission and are the infrared equivalant of the Palomar and SRC Schmidt surveys.

Two major problems afflict the first set of images. First, the zodiacal emission varies both spatially and temporally, severely hampering the job of obtaining accurate fluxes for Galactic objects. Second, uncorrected variation at the 2-4 per cent level in detector offsets and responsivities led to inaccurate photometry and to stripes in the images that limited their sensitivity. New images will be produced by coadding and destriping carefully recalibrated data for a given piece of sky after the subtraction of a zodiacal cloud model. IPAC will produce a single set of images with 1.5' pixels that will be six times more sensitive than the original images. An example of the difference between the new and old all-sky images is given in Figure 2a and b which show views of the Pleiades in the current form and after using one of the prototype destriping techniques. Figure 2b hints at the improvements expected in the new images. Structures, such as faint 12 μm cirrus, that were impossible to measure previously will be routinely detectable on the new images.

The software to produce the new images is still being developed as different flat fielding algorithms are now being tested. It is anticipated that the testing of algorithms and prototype production will last another year. The new images will be released in stages over the course of a year beginning in 1989.

2.3.2 Zodiacal History File

The so called "Zodiacal Observation History File" presented a scan-by-scan view of the sky with a synthesized 0.5 degree beam. Reseachers have used the Zodiacal History File to study the zodiacal dust cloud and, in conjunction with other low resolution surveys in CO,HI and the radio continuum, the large scale structure of the Galaxy. One particularly intriguing result is an isotropic 100 μm background of 2 to 5 MJy/sr [13,14] that possibly remains in the data after solar system and galactic components have been subtracted. The existence of a cosmological background at 100 μm is obviously a very exciting possibility if it can be verified.

The problem of the absolute intensity of the sky is a difficult one since the IRAS instrument had no absolute photometric reference for extended emission. However, we have tried to incorporate all known instrumental

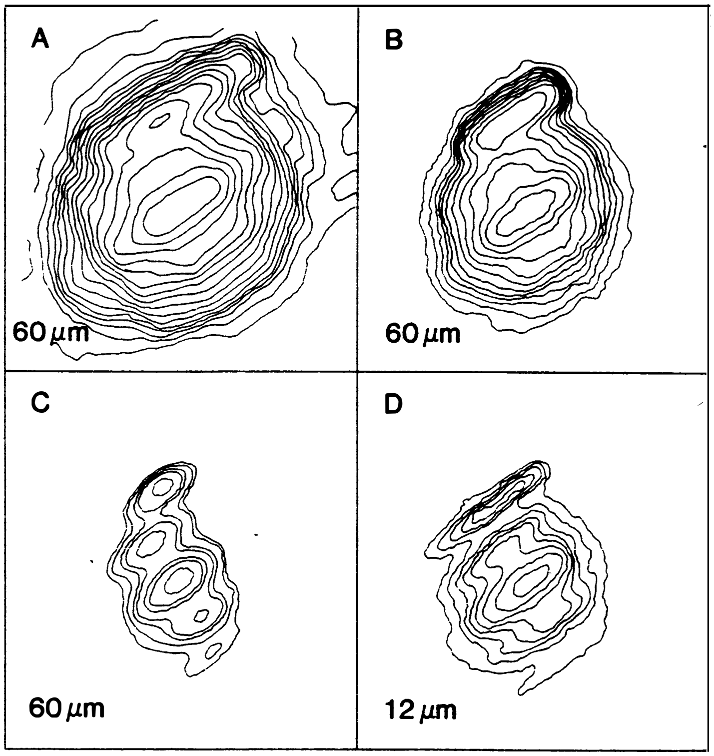


Fig. 3. Panels a,b, and c show 60μm detetectors. Figure 3d shows the unenhanced IRAS 12 μm, with twice the spatial resolution of the original 60 μm data in the "in-scan" dimension, illustrating the strong correspondence between the enhanced 60μm data and the 12 μm image.

effects into a newly calibrated set of data for use in a new Zodiacal Observation HistoryFile and the moderate resolution images. The new Zodiacal History File will be ready for release in the summer of 1988 and will give the best view of the absolute emission from the infrared sky until the flight of the Cosmic Background Explorer (COBE).

2.4 High Resolution

The IRAS focal plane contained fairly large, rectangular detectors to support the primary project goal of surveying the entire sky at the greatest possible sensitivity, completeness, and reliability. While high spatial resolution was not built into IRAS, several features of the focal plane combined with the instrument's stability - and absence of atmospheric distortion - enable diffraction limited imaging for brighter sources. Half overlapping detectors in the focal plane centre and smaller detectors along the edges were used to reduce position errors for point source detections. These overlaps can be used to synthesize smaller detectors - essentially two arcmin in the cross-scan direction. These overlaps and in-scan resampling (of the over-sampled pointed observation data) allow the data to be gridded as a two arcmin gaussian beam. Image reconstruction techniques such as "maximum entropy" are being developed to display the data as a 30 to 60 arcsec gaussian beam in all bands.

Figure 3 shows an example of the potential improvement in the spatial resolution of the IRAS data. Figure 3a shows the 60 μm image produced by standard processing of data for the galaxy M51+NGC 5195. The two galaxies are only partially resolved. Figure 3b shows the result of remapping the original IRAS into a uniformly sampled image. A significant amount of high spatial frequency information in the original data has been preserved; no spatial frequency restoration has yet been applied. Figure 3c shows the result of the application of the Richardson-Lucy algorithm to the image in Figure 3b, using the measured point spread functions of the 60μm detectors. Figure 3d shows the un-enhanced IRAS 12 μm image, with twice the spatial resolution of the original 60μm data in the "in-scan" dimension, illustrating the strong correspondence between the enhanced 60μm data and the 12μm image.

IPAC currently plans to make enhanced resolution algorithms, along with the expertise necessary to apply them to the IRAS data, available to the user community in stages, as required by the increasing difficulty of each successive step. IRAS pointed observations produced with the uniform remapping algorithm of Figure 3b were made available to general users in the October 1987. A tested and documented version of a resolution enhancement algorithm like that illustrated in Figure 3c will be released in the fall of 1988 and a generalisation of these algorithms to IRAS survey data is planned for release in late 1989. We have no plans to use any of these algorithms in mass production, since processing each piece of sky requires careful scientific and technical scrutiny by a user knowledgeable in the workings of the algorithms. Instead, these techniques would become part of the suite of analysis tools available at IPAC.

3. THE GUEST INVESTIGATOR PROGRAMME

When IPAC was established, we were given the new assignment of supporting the astronomical community in doing research with the IRAS data products that we had just released. Thus our first task was to create an environment in which non-IRAS astronomers could come to our facility and work with the IRAS data. Since we had fewer than six months in which to do this before the arrival of the first General Investigators (GIs), we had to put together a system as rapidly as possible! Basically, we had to reorient our "catalogue production facility" into an "analysis facility". The major steps involved in this process were:

1. Reorient our staff from catalogue production and analysis tasks in a flight project context to a supporting role for many ad hoc analysis tasks.
2. Develop a catalogue and non-image data analysis facility on our existing IBM 3032 computer.
3. Develop an image processing facility.

We were able to perform steps one and two successfully by the first arrival of GIs. We had a rudimentary image processing facility at the start, but it required another year before we successfully created a first class image processing facility.

3.1 GI Support at IPAC

IPAC is open to any astronomer doing legitimate research. Most IPAC visitors gain access and funding via a peer-reviewed selection process. Others can be accommodated on a non-interference basis by submitting a one or two page letter proposal to the IPAC Chief Scientist.

There are three kinds of data processing support that IPAC has to offer: coadditions of raw data for detailed views, image processing, and catalogue analysis. We have two main coaddition processors that give a factor of three sensitivity gain over the released IRAS products and these are often the main object of the GI's attention. The one dimensional coaddition, ADDSCAN, collects all detector scans that passed over a selected point – typically eight to 12 detections – adds them all into a normalised histogram and displays the result in several forms. This is our highest resolution product and is best used for point or slightly extended sources of known position. This one dimensional approach works well because in the other dimension the IRAS detectors are significantly larger. This has become a very popular product and is automated to the point that we can currently produce several hundred per week. As the Faint Source Survey becomes available, the use of the 1-D coaddition should decline somewhat.

The two dimensional coaddition, "Survey Coadd," is an evolution of the primary mission Additional Observation processing. All scans covering a target field are coadded onto a common grid to produce higher resolution (.25 by .25 arcmin pixels at 12 and 25μm) maps of the field. Usually two degree square fields are done, but larger areas can be accommodated. As the new Sky Brightness Images and high resolution products become available, Survey Coadd will probably become obsolete. Both the 1-D and 2-D coadditions operate on the basic mission detector and pointing data.

Image processing is provided on three Jupiter/Microvax work-stations which use IPAC's own software. The standard image products from the mission – the 16.5 degree plates, the Additional Observations, the survey coadds and the ZOHF – as well as user provided images can be displayed and manipulated. Images can be compared, differenced, ratioed, stretched, sliced, histogramed, Fourier transformed, flattened and otherwise tortured to squeeze all the available science (and sometimes more!) from them.

Several programs are available to access and analyse IRAS catalogue data and compare it with other astronomy catalogues. The IRAS catalogues include all those listed in Table 1, the Working Survey Data Base (which contains more detailed information on PSC sources) and (coming soon) the Faint Survey Data Base. About 40 other astronomy catalogues are on line. The analysis programs are used to select sources on any criteria, compare the selected sources to other catalogues, and then display them in various ways. Colour-colour, Log N/Log S, map, and overlays for the optical sky survey photographs are some of the plots supported.

One of the best received features of IPAC support is the GI's "friend". Besides the user's guide, computing account, desk, etc. each visitor is assigned a friend – one of our Ph.D. astronomers – who reviews the visitor's plan and advises on data analysis, interpretation, and problems. The friends have been quite serious about assuring that each GI's visit is productive and this may be the most important single reason for the success of the GI program.

3.2 New IPAC Data System

Almost simultaneously with the establishment of IPAC, we began planning for the creation of a significantly better environment for analysis by outside investigators. We acquired a CDC Cyber 180/850 to serve as the nucleus of a new analysis system. We began the development of the new system using the experience we had gained through the support of the first GIs.

The design of the new data system on the Cyber follows closely the approach of the Birmingham group as given on a previous JBIS article [15], although the approach was completely independent! The basic principles of instrument independence, modularity, flexibility, and efficiency are the same. These principles are achieved in the same manner through what Birmingham calls a "standard form" for data storage and what IPAC calls a "data table file".

Support of the GI on the Cyber is greatly improved in several areas. For catalogue work, running on a truly interactive machine is a great time saver. Sources selected during searches are logged into table files where any parameter can be accessed for plots, calculations or further selection. Results of any step can be displayed - listed or plotted - on the screen to verify or reiterate or redirect that step. An extensive menu of functions are available for user selection or one's own manipulations can be easily coded and executed. Building the data table files, performing logical operations, and displaying results are all enhanced by the system's control of most overhead functions, thus freeing the user of computer system chores and enabling full attention to astrophysical issues. For coaddition work, the new system speeds production through a new job control executive that more optimally loads plates and runs jobs. As our network and optical disk storage capabilities develop, the Cyber is expected to support the computationally intensive parts of image analysis. Overall, this is a powerful new data system.

3.3 The IPAC Database

The 80 Gbyte mission data base is the foundation which supports both the continuing science analysis and the new product development. The IRAS survey data is maintained at IPAC in several forms that reflect various levels of data reduction. The most basic record is the time ordered flux history of the 59 working detectors (out of 62) in four infrared wavelength bands (12,25,60 and 100 μm)and the associated pointing information. These are stored on some 570 tapes corresponding to the twice daily downloads that were received from the satellite during its 285 day mission.

Because redundancy of coverage was intrinsic to the survey strategy, a typical area of the sky was observed six times and recorded on 3-6 different tapes. Sources at high ecliptic latitudes tend to have their observations spread over more tapes because the scan overlap increased with latitude. The extreme cases are at the poles where a hundred tapes had to be read to reprocess these highly over-scanned areas. This made a position-sorted version of the mission data very attractive. We sorted the detector and pointing data into 1716 plates using an extended ESO equatoral system with five degree centre to centre separations. Each plate covers 7.3 degrees by 7.3 degrees to give sufficient margins, so the data volume expanded by over a factor of two. It is well worth the extra storage because the plates allow access to all coverages of a target with only a single tape mount.

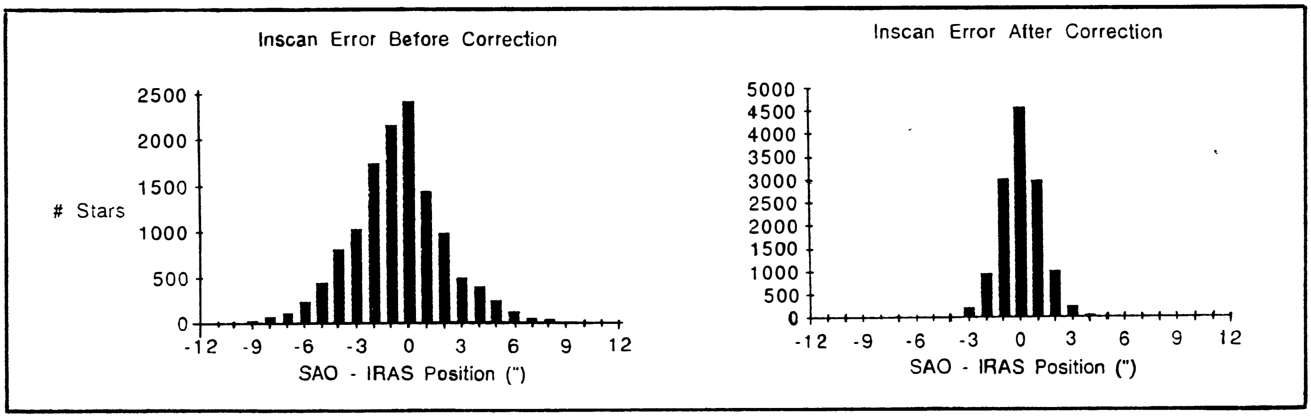


Figure 4. The distribution of errors in the seconds confirmed positions of stars from the SAO catalogue is shown before and after incorporating "infrared feedback" into the reconstruction of the pointing of the telescope The 1σ deviation in one observation before correction is 3"; after correction the deviation is only 1.2".

A more fundamental improvement to the mission data base has been to improve the pointing history of the telescope - completed in 1987. Refinement of the onboard pointing information was accomplished by identifying 12 μm detections with stars of well known position and using the difference between the measured and known positions to correct the Boresight Pointing History File. This improvement was done primarily to support the Faint Source Survey. While the improved pointing helps in the coaddition for the FSS sources, the coaddition process somewhat erodes the accuracy of the final positions through the binning necessary for the coaddition. All current processing at IPAC uses this new pointing history whenever possible. The result is that new analysis of IRAS sources can have improved pointing reconstruction that enable a reduction in the area of the uncertainty ellipses by a factor of 2 to 3 (Figure 4). This improved pointing has not yet been factored into refined IRAS catalogue positions.

A third enhancement to the basic mission data base is the improved calibration. The previous IRAS calibration suffered from detector hysteresis, which increases the detector responsivity following the observation of bright objects, especially at 100 and 60 μm and especially near the Galactic plane. Sources near the plane showed abnormally low or high fluxes depending on their distance before or after the plane crossing. The improved calibration corrects most of that detector hysteresis error and generally improved the absolute (dc) calibration through refined treatment of the routine on-board calibration events. The main beneficiary of the improved calibration will be the second generation of image products, but it is now available for general use as well.

The IPAC staff is a vital supplement to the IRAS mission data base. Personnel who worked on the IRAS mission preparation, execution, and analysis (up to 11 years experience in some cases) are on the IPAC staff and in addition to their own research or engineering duties are available to provide expert advice on data interpretation. This is an invaluable and irreplaceable repository of knowledge about IRAS.

4. NEW IPAC PRODUCTS

4.1 Nasa Extragalactic Database

Several members of the IPAC scientific staff became interested in creating a large database of catalogued extragalactic objects as an outgrowth of producing the IRAS catalogues. They proposed the establishment of a "Nasa Extragalactic Database" which would reside at IPAC and be made remotely accessible to astronomers world-wide. IPAC is now in the process of establishing this database [16].

The Database will make available data from extragalactic catalogues, as well as data and references from published articles on extragalactic objects. The goal is to remain current in the literature, and work toward completeness in past literature. The impetus for the Extragalactic Database derives from the need for a central archive accumulating all published extragalactic data, organised for fast retrieval and flexibility, and accessible to all astronomers.

All data that can be summarised in a few numbers will be included and those that cannot be briefly summarised will be referenced with adequate description attached. The Database will also provide references to observing logs and data archives kept by observatories or other facilities. The basic capabilities will consist of 1) literature searches and summaries of published data for objects specified by name; 2) positional searches for all objects in the vicinity of a specified location on the sky; and 3) keyed searches for all objects whose observed parameters satisfy a given set of conditions.

The database is intended to be parallel and complementary to the stellar data service SIMBAD (Set of Identifications, Measurements and Bibliography for Astronomical Data) offered by the Centre de Donnees Stellaires at the Observatoire Astronomique de Strasbourg. We therefore rely on collaboration with the Strasbourg Centre, and have evolved a preliminary understanding concerning exchange of data and expertise. We expect that the facility will be open to remote access by astronomers in mid 1989, roughly eighteen months after starting work on the project.

The next three topics describe products currently in various stages of planning. We now see these as the final refinements to the IRAS data. Ideas for worthwhile products beyond these may or may not develop in the future. Regardless of that, IPAC plans to continue to support IRAS database users for as long as such support is productive.

4.2 Improved Positions for IRAS Sources

The original processing of the IRAS Point Source Catalogue used positional information derived by observing one to three visible stars during the course of each 20 minute scan. Even though the derived positions were remarkably good, with typical errors for a 0.5 Jy source at 12μm of 3"×16", the problem of identifying weak IRAS sources with objects on radio or optical maps becomes severe for the faintest sources. Use of the improved pointing information discussed in Section 3.3 will translate the improved pointing history into improved catalogue positions and uncertainties.

A major legacy of IPAC should be the determination of the positions of all IRAS sources with the greatest possible accuracy. Current IRAS error ellipses represent several beam diameters to the current generation of large millimeter wave telescopes and interferometers. Improving the accuracy of the IRAS positions will increase our ability to compare features in maps at various wavelengths and would increase the efficiency of follow-up observations.

We are presently analysing two methods of improving the positions of IRAS sources. We can either rerun the programmes that produced the PSC in the first place, but modified to use the improved knowledge of the telescope boresight. Or, we can use the Faint Source Catalogue to determine this positional information. Both methods have positive and negative aspects. We will be able to decide on an approach once we have fully analysed the first release of the FSC. Either method would require about one year of computing at IPAC to complete.

4.3 Optical Identification of IRAS Sources

Some 65 per cent of the objects in the PSC are not associated with objects in other astronomical catalogues. However, a number of studies have demonstrated that most of the sources away from the Galactic plane and dark clouds have optical counterparts on deep photographic surveys such as the Palomar and SRC Schmidt surveys [17,18]. FSC and FSS plates will contain an even greater fraction of uncatalogued sources than the PSC. The science to be gained by identifying objects from the various IRAS catalogues with visible objects is great. The study of quasar evolution and the opportunity of finding a brown dwarf star are but two of many exciting possibilities. We plan a programme of finding optical counterparts for all IRAS sources above some Galactic latitude cutoff, approximately $|b| \geq 20$ degrees. We identify three goals for this optical identification programme.

1) The optical identifications will increase our confidence in the weakest FSC sources and let us reliably find objects at the faintest flux levels. Instead of selecting objects at the 4-5 σ level from the FSC data, the presence of an optical counterpart wil let us go down to the 3-4 σ level and catalogue tens of thousands of new IRAS objects.

2) The combination of optical and IRAS observations provides a powerful tool for understanding the nature of the objects detected first by IRAS. For many classes of sources the relationships are well established between optical and IR counterparts. For example, the combination of IRAS colours and two photographic magnitudes allows one to separate infrared quasars from mass loss stars [19].

3) It should be possible to use the optical data to obtain improved positions as well.

We plan using a combination of the SRC survey in the Southern Hemisphere and the new Palomar survey (POSS2) for the Northern hemisphere. The extra 1-2 magnitudes of sensitivity gained in POSS2 over the original POSS plates ensure that almost 100 per cent of the extragalactic and high latitude Galactic objects detected by IRAS will have optical counterparts. It should be pointed out that the relatively small fraction of the objects that cannot be identified on the first POSS survey are just those objects that are probably the most interesting, i.e., those objects with a high ratio of infrared to visible luminosity. For example, the very reddest extra-galactic objects have turned out to be infrared galaxies with luminosities approaching those of the quasars [20,21] while the most extreme stellar objects are among the coolest known carbon stars.

We plan to study the optical identification problem during the next year. Based on the current estimates, the IRAS/optical catalogue would be published by 1992.

4.4 Smaller Scale Tasks

In the next year we plan to study two additional tasks involving significant reprocessing of the IRAS data. The first of these is to measure the brightness of moderately extended objects ($\leq 8'$) more accurately than was done in the Small Scale Structures catalogue. The first pass through the data was made with simple algorithms that produced more dispersion in the fluxes for star formation regions and external galaxies than is desirable. The ADDSCAN tool could be used to make improved estimates of the fluxes and sizes of some 10,000-20,000 objects thought to be somewhat extended.

A second task we are presently studying is the possibility of reprocessing the Additional Observations. IRAS made over 10,000 maps covering more than 1,000 square degrees that are up to five times more sensitive than the main survey. New techniques for coadding the data in these special scans and for deriving better positions for sources extracted from them at possible. What is not yet certain is the degree of improvement. If a factor of about two improvement in positional accuracy or sensitivity is possible, then we would proceed.

Finally, as part of the routine database management we plan to merge all of the IRAS catalogues into a single catalogue. The catalogues to be combined include the Point Source Catalogue, the Faint Source Catalogue, the Serendipitous Survey Catalogue, and the Small Scale Structure Catalogue. This effort would involve more than a simple concatenation of source lists, since we would try to determine which database provided the best information for each source.

5. CONCLUSIONS

Several factors have contributed to the post-mission success of IRAS:

1. The excellent stability and performance of the IRAS satellite and the resulting mission data base.
2. The retention of the team that developed the original catalogues and images ensures a corporate memory of all aspects of the satellite, mission, and data reduction.
3. The fact that NASA chose to support IPAC.
4. The enthusiastic response of the astronomy community to the unique IRAS view of the sky.
5. All of these factors have led to vigorous, multi-faceted programme of research support and product development that promises to have a lasting impact on our understanding of the universe.

ACKNOWLEDGEMENTS

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FUTURE SPACE MISSIONS IN GAMMA-RAY ASTRONOMY

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In the period leading up to the end of the century a number of space borne gamma-ray telescopes are expected to be operational. It should be an exciting era for the high energy astrophysicist, since these missions have the corporate capacity to advance this very fundamental branch of observational astronomy from the early exploratory phase to a level in which highly sophisticated and detailed measurements are possible on large numbers and a wide variety of astronomical objects. From past experience, when similar advances have been made in a 'new' waveband, the results have led to important discoveries and a more profound understanding of the universe. Gamma-ray astronomy, with its intimate connection to nuclear and particle processes, is unlikely to be different.

1. INTRODUCTION

The dividing line between the X-ray domain of the electromagnetic spectrum is somewhat artificial and is dictated mostly by experimental techniques tied to the photon interaction mechanisms. A value corresponding to energies in excess of 100 keV has often been considered an appropriate point at which to define a gamma-ray photon. The necessarily close relationship of these energetic photons with their parent particles and fields provide a direct probe of the high energy physics phenomena which take place in both the interstellar space and in the vicinity of compact objects. This intimate relationship is further highlighted by the capability to make direct observations of nuclear processes by means of discrete gamma-ray line emissions.

The development of an effective observational technique in the gamma-ray domain has been slow, due to the harsh experimental difficulties and intrinsically low cosmic signal to noise ratios encountered in past instrumentation. However, the successful SAS-2 and Cos-B missions have completed an important exploratory stage in the high energy region (> tens of MeV) yielding a gamma-ray picture of the Galaxy in fair detail and essentially opening the extragalactic sky. In the MeV spectral range, results are mainly derived from balloon and limited satellite experiments but show that a wide variety of galactic and extragalactic objects are low energy gamma-ray emitters. In fact, emission close to 1MeV seems to be the rule for many types of diverse astronomical objects. In the extragalactic context these include the nearest radio galaxy (Cen A), the nearest and brightest examples of Seyferts andd quasars (e.g. NGC 4151, 3C273). A broad band spectral look at these objects provides a convincing proof that the majority of their power is emitted in the gamma-ray domain and that the summed contributions of the 'gamma-ray galaxies' probably account for the observed cosmic diffuse gamma-ray background. On the galactic side, again a variety of object types are gamma-ray emitters: compact objects in the form of pulsars, one of which (the Vela) has been obsrved to emit linearly polarized gamma-rays; the Crab SNR; X-ray binary systems (e.g. Cyg X-1, Cyg X-3, Her X-1, Vela X-1); diffuse emmissions from local cloud complexes (ρ Oph etc.) as well as interstellar matter. In the latter case the gamma-rays probe the interactions of energetic particles with the ISM and fields and are not hampered by absorption in the local gas.

One special aspect of gamma-ray astronomy is the possibility of probing nuclear and elementary particle processes directly by means of spectroscopy. The two most noted examples to date, are the $e^{\pm}$ annihilation radiation from the Galactic centra and the 1.809 MeV emission coming from the decay of $^{26}Mg^{*} \rightarrow {}^{26}Al$ which is derived from recent ($<10^{6}$ yr) nucleosynthesis in the Galaxy. Moreover, as a result of the first steps in gamma-ray astronomy two new classes of objects have been discovered (but not yet identified) both with the property of emitting by far the largest fraction (99,9%) of their luminosity in the form of gamma-rays. There are the gamme-ray bursters and the high energy gamma-ray source 'Geminga'. Both classes appear to be compact, and emit 1000 times more energy in gamma-rays than in X-rays. A situation reminiscent of the discoery of the first bright X-ray sources, the study of which led to the relevation of a completely new class of astronomical entity.

The wavelength of gamme-ray photons is extremeley short, less than interatomic distances is solids. Consequently in order to achieve imaging systems classical wave techniques cannot be employed. The first phase of instrumentation has relied on the kinematics of the associated particle interactions i.e. the 'double Compton' method at low energies (<10 MeV) and projection of the resultant electron-positron pairs at higher energies to estimate the direction of the incidence gamma-ray. Both of these methods are employed on the forthcoming Gamma-Ray Observatory (GRO). The second phase, which is now ready for exploitation, will involve sophisticated aperture modulation techniques which have made fine quality gamma-ray imaging a practical reality. There are three gamma-ray astronomy space projects planned for the immediate future: Gamma 1, SIGMA and GRO, and a further mission (GRASP) under study as a prospective ESA space astronomy mission. The first three projects represent the first steps of the transformation of this high energy discipline from the explorer class to the first imaging generation. GRASP is a more advanced mission which, with the refinements of high sensitivity, fine angular resolution, a nuclear spectroscopy capability, and polarization sensitivity, will be capable of generating

sophisticated and detailed measurements on a large number and wide variety of astronomical objects. Such studies will create novel and varied astrophysics. Thus within the next decade gamma-ray astronomy offers the opportunity to open up a new window on the Universe including the possible existence of regions of antimatter as well as the direct study of physical processes in the vicinity of massive black holes.

2. THE GAMMA-RAY OBSERVATORY

The Gamma-Ray Observatory (GRO) is a NASA mission to be launched in a free flyer from the space shuttle. (Bertsh 1984). The GRO consists of a support platform and four instruments to cover the energy range 50 keV to 30 GeV as described below. The scientific objectives of GRO aim to build upon the current observational status of gamma-ray astronomy. The typical performance parameters for each of the four instruments are shown in Table 1. The major emphasis of GRO has been a significant (×20) increase in sensitivity over and above past gamma-ray missions. The spectral resolving power and angular resolution capability of the instruments remain similar to that of past missions such as Cos B and SAS II. The major impact of GRO will be to increase the number of detected gamma-ray sources (× 10 to 100), to measure their temporal characteristics (sub-millisecond), to make some preliminary polarimetry studies but not to produce a significant improvement in the detailed spectral information or source locations. Thus GRO provides an invaluable next step in gamma-ray astronomy, it will point the astrophysical directions to follow for the future telescopes with better spectroscopy and imaging power which are likely to follow this mission.

The GRO instruments require a significant increase in size over earlier satellite gamma-ray systems to achieve the desired increase in sensitivity. It was decided to combine the instruments into one mission because of the great scientific value of studying such a wide range of the gamma-ray spectrum of any object at the same time as well as any temporal variations. Each experiment has been chosen such that its sensitive energy range of operation overlap those of the nearest neighbours, so allowing continuity of spectral measurements.

The GRO spacecraft has a total weight of 14 tons of which 6.0 tons will be used as instruments. It will operate as a free flyer satellite, after a shuttle launch, at an altitude of 400 km and with an inclination of 28.5 degrees. This altitude is chosen in order to reduce the particle fluxes during passages through the South Atlantic anomally. The propulsion system will raise the vehicle from the shuttle orbit and maintain this altitude for 2 years with the possibility of retrieval or recovery by the Shuttle. Celestial 3 axis pointing to any point on the sky will be maintained to an accuracy of ±0.5 degree. Knowledge of the pointing direction will be determined to an accuracy of 2 arc minutes and the absolute timing accuracy of gamma-ray photons will be 0.1 milliseconds. The GRO has been designed as a Principal Investigator class of observatory. This is largely due to the esoteric nature of the analysis and interpretation of the data from each instrument. However, the science team have developed an 'Associate Observer programme' to allow selected outside scientist to work closely with the participating institutions for extended periods on the data analysis from specific sources.

The four instruments incorporated on the payload are:

2.1 The Orientated Scintillation Spectrometer Experiment (OSSE)

The OSSE has been designed to observe astronomical sources over the energy range 0.05 to 10 MeV (Kurfess *et al* 1984). The instrument consists of four identical detectors (Fig 1a & 1b) mounted on a single axis control system that enables offset pointing with respect to the observatory over a range of more than 180 degrees. The large drive range of each quadrant allows all detectors to be reoriented to a second source for that portion of each orbit during which the primary source is occulated by the Earth. Furthermore the detectors are operated in coaxial pairs such that whilst one pair is observing the source the other two can be measuring the background from an offset position. Periodically the two sets of detectors can interchange their orientation to provide a more reliable background subtraction.

A 33 cm diameter NaI(T) - CSI(T) phoswich provides the primary gamma-ray detection element of each quadrant. The NaI(T) detector element is 10cm thick and pulse shape discrimination is used to distinguish energy deposits in the NaI(T) from those in the CsI(T) portion of the phoswich. An annular shield consisting of four 7cm thick CsI(Na) segments, together wioth the CsI portion of the phoswich, provides an actie anticoincidence shield. A slatted tungsten collimator defines the 3·8 degrees × 11·4 degrees field of view and provides the FWHM angular resolution. The spectral resolution is typically 8 per cent FWHM at 0.661 MeV and 3.2 per cent at 4.43 MeV.

2.2 The Imaging Compton Telescope (Comptel)

A schematic diagram of the COMPTEL detector system is shown in Fig.2. The instrument consists of two detector planes set a distance of 1.5m apart and surrounded by a series of anticoincidence systems (Schonfelder *et al*, 1984). The upper level is constructed from an array of NE 213 liquid scintillators and the lower level employs NaI(T) crystals. The instrument operates over the spectral range 1-30 MeV and has been designed to minimise the unwanted background noise usually experienced in the nuclear gamma-ray emission domain. Events are

Parameter	OSSE	COMPTEL	EGRET	BATSE
Energy range (MeV)	0.05-10	1.0-30	20-3 10^4	0.05-20
Energy resolution (E/ΔE)	12 at 0.66	15	7	15
Max. sensitive area (cm^2xeff)	2685	50	2000	14000
Aperture	100 sq.deg.	0.6 sr	0.5 sr	4π sr
Angular res (FWHM)	3.8 × 11.4 deg.	2 deg.	4 deg. at 100 MeV 0.5 deg. at 2 GeV	deg
3σ sensitivity mCrab in 10^6s	10	30	10	6 10^{-8} erg cm^{-2}
3σ line sens. ph cm^{-2}s	2 10^{-5}	3 10^{-5}	–	–
Temporal res.	0.1ms	0.1ms	0.1ms	ms
Polarimetry	No	Yes	Yes	No

Table 1. Typical performance parameters of the GRO instrument.

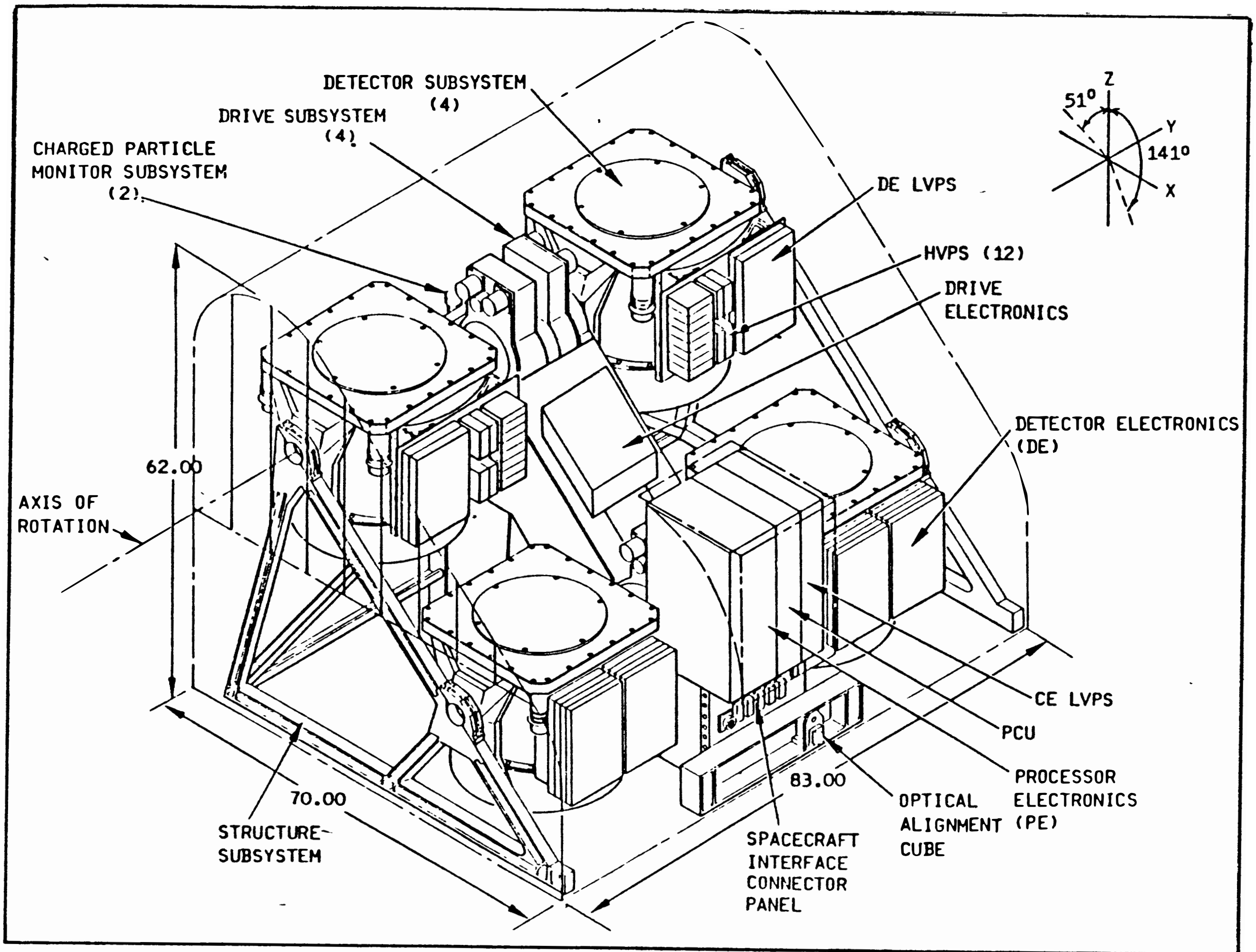


Fig 1a The Orientated Scintillation Spectrometer Experiment (OSSE) on board the GRO spacecraft.

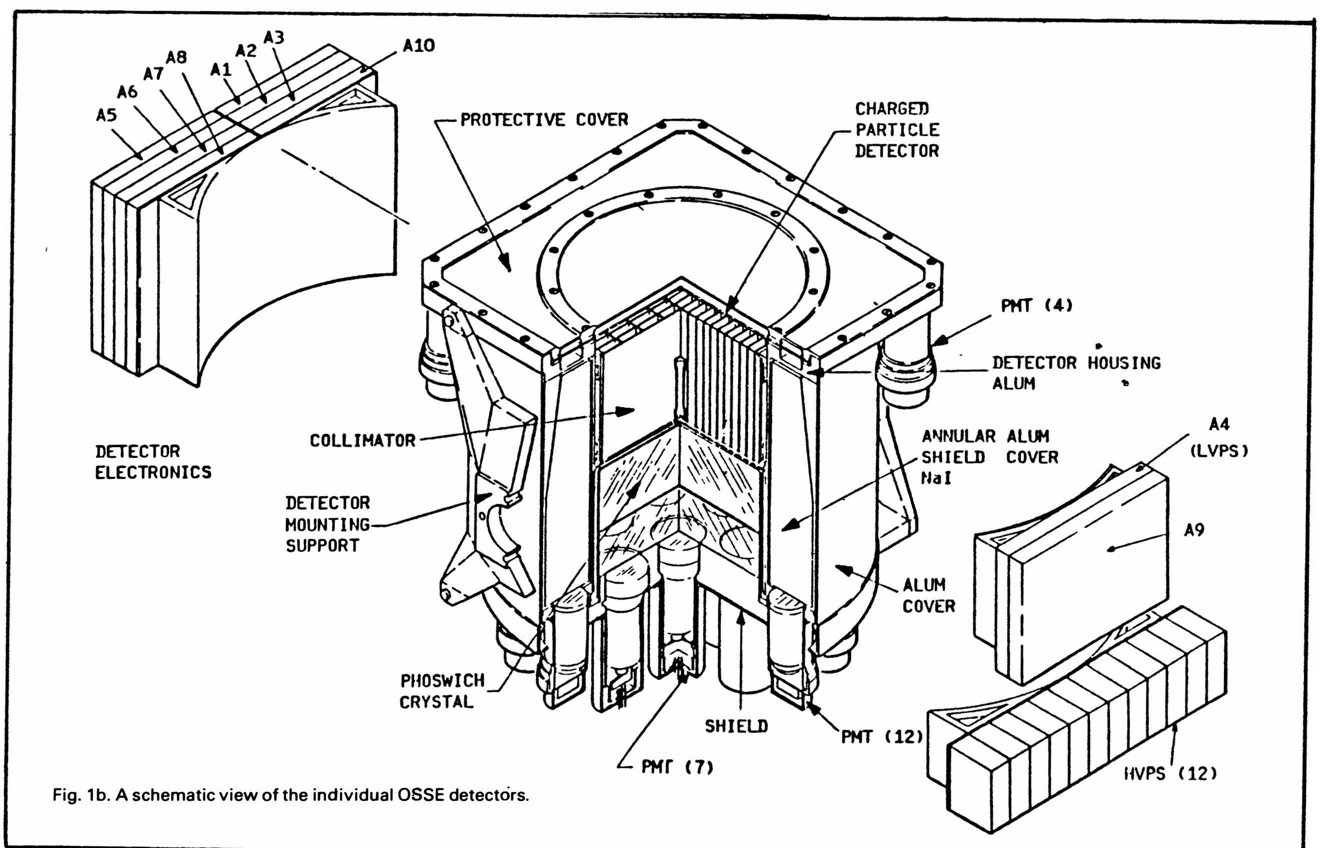


Fig. 1b. A schematic view of the individual OSSE detectors.

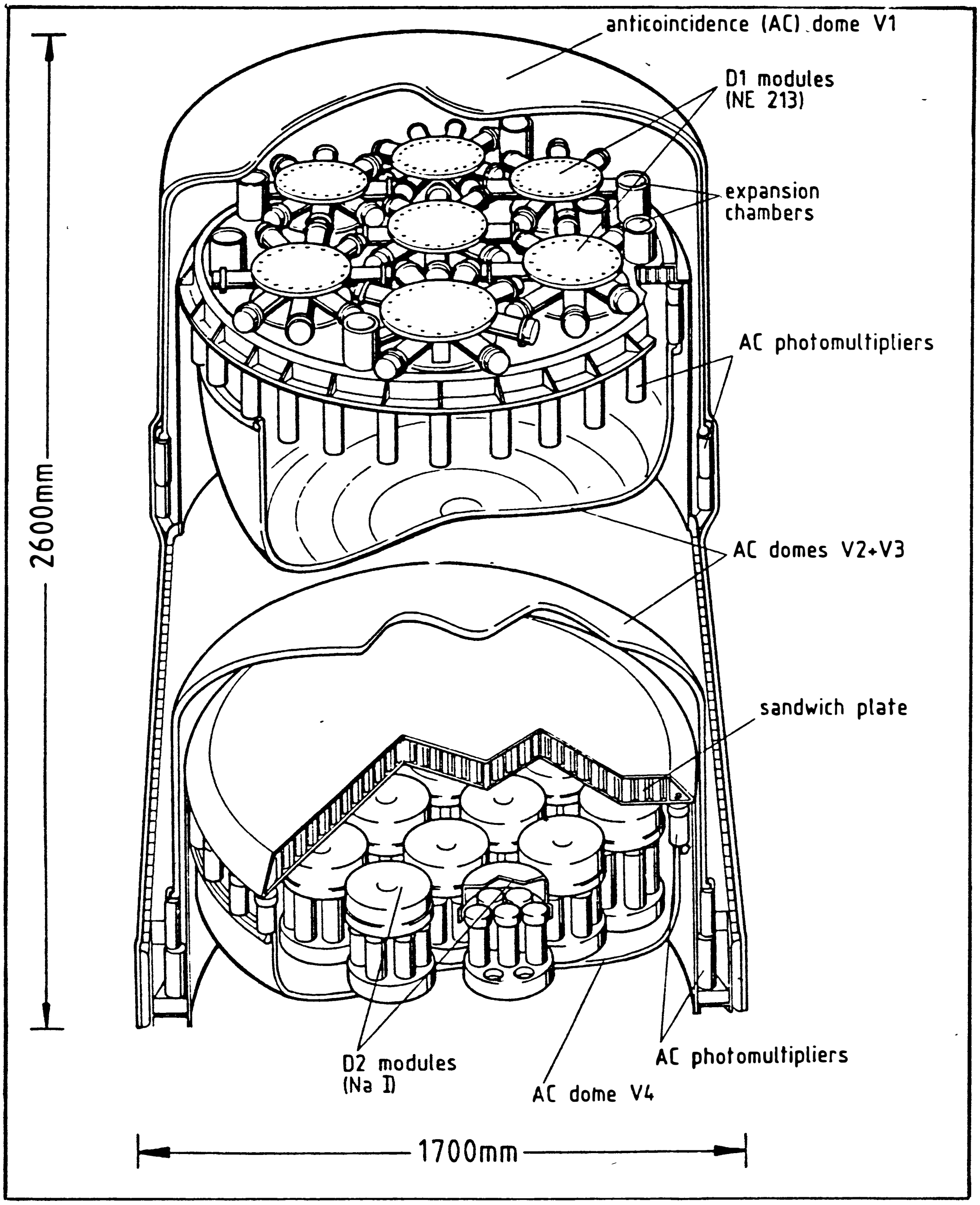


Fig. 2. Detector Assembly of the Imaging Compton Telescope (COMPTEL).

selected on the basis that a gamma-ray photon is Compton scattered in the upper level and that the secondary photon subsequently interacts in the lower level detection plane. The locations and energy losses of both interactions are measured and are used to determine the energy and direction of incidence of the incoming photons on the basis of the Compton kinematical relationships. The FWHM angular resolution of the instrument is about 2 degrees within a field of view of ~1 steradian and the energy resolution is typically 6 per cent FWHM in the MeV range. The effective area of the telescope is 20-50cm^2 depending on the photon energy.

In order to suppress unwanted background noise a number of strict requirements are placed upon the candidate gamma-ray events: coincidence between the two detection levels; no coincidence pulse from the veto system; delayed time of flight coincidence between the upper and lower levels; pulse shape discrimination in the NE 213 pulse (to reject neutron scatter). The system has the ability to study the polarization characteristics in detected photons and has a gamma-ray burst mode of operation.

Observations with COMPTEL will clearly exploit the high sensitivity of the instrument and wide field of view to provide the first high sensitivity exploration survey of the gamma-ray sky at nuclear gamma-ray wavelengths. The clean event selection should make the instrument particularly good for the study of the cosmic diffuse background. COMPTEL will pave the way for the next generation of instruments which will have a fine spectroscopy and imaging capability.

2.3 The Energetic Gamma-Ray Experiment Telescope (EGRET)

EGRET is designed to operate at the top end of the GRO spectral range $20 < E < 3\ 10^4$ MeV. A schematic view of the instrument is shown in Fig 3. The conceptual design of this telescope is based around the use of a spark chamber system which has a geometric area of 6400 cm^2 (Hughes

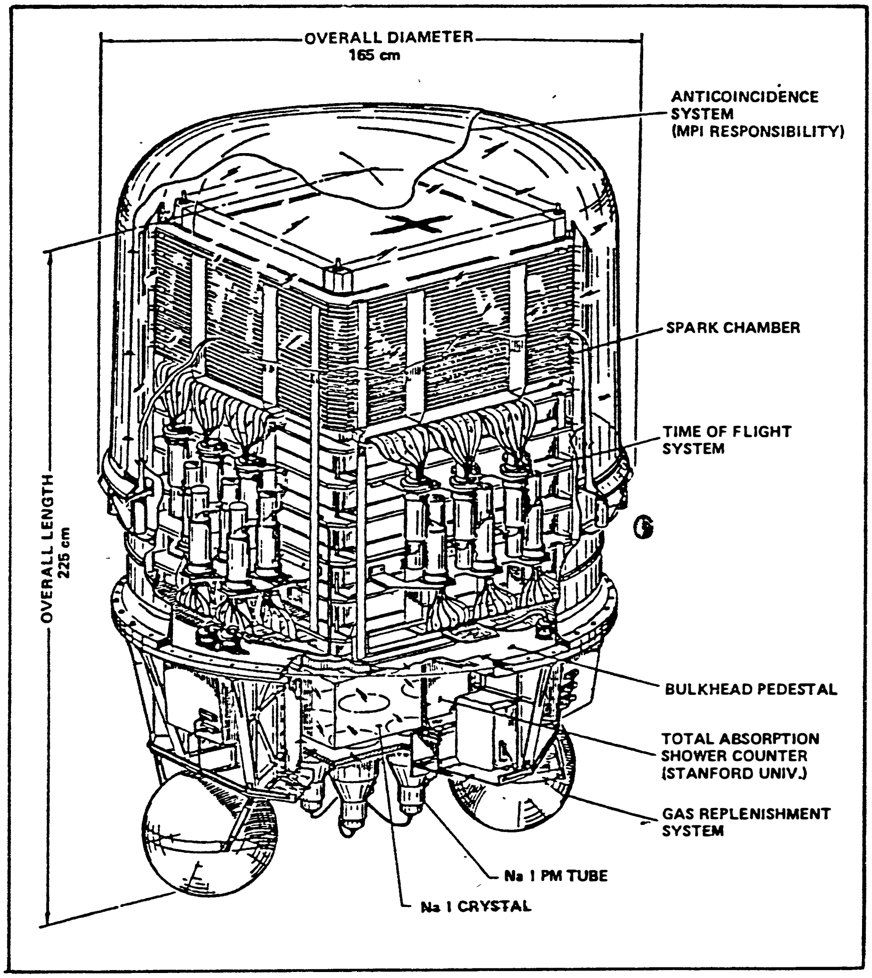


Fig. 3. High Energy Gamma-ray Telescope (EGRET).

et al 1980). Incident gamma-rays which enter the forward aperture of the instrument are efficiently (15 per cent) converted into electron-position pairs in one of the 27 thin (0.02 radiation length) tantalum plates which are interspersed with the spark modules. The tracks of the electrons are subsequently followed through the system by means of a 3D reconstruction of the spark positions. "Good" events appear as an inverted "V" and a kinematical analysis of the electron trajectories enables an estimate of the direction of the incident photon to be made. The angular resolution of the telescope is typically 4 degrees FWHM at $E_\gamma = 100$ MeV and drops to about 0.5 degrees at $E_\gamma = 2$ GeV.

Gamma-ray events are selected on the basis that at least one electrom is detected as a downward moving particle by the directional time of flight scintillation telescope placed immediately below the main spark chamber. No signal must be present in the large plastic anticoincidence scintillation dome which surrounds the upper portion of the telescope. Thus unwanted charged particle events are efficiently rejected. Provided the gamma-ray selection criterion is met a high voltage pulse is applied to the spark modules and subsequently the event data is recorded. Again, as with COMPTEL, considerable care has been taken to ensure the 'clean' selection of genuine gamma-ray events. The time of flight system efficiently rejects backward moving charged particles which do not reach the veto dome. A series of six additional spark modules are located in the space between the time of flight telescope in order to provide further information on the progress of the electrons. As a further refinement each scintillation plane of the time of flight system is constructed from a 4×4 array of independent detectors. Coincidence limitations from selected elements enables the aperature to be dynamically varied to reduce unwanted background such as that derived from the Earth's limb as it passes through the field of view. As a final resort, careful inspection of the spark chamber pictures can assist in the rejection of events which have a dubious parentage.

The energy of the gamma-ray photons is measured by means of an eight radiation length thick NaI(T1 scintillation crystal placed below the lower time of flight scintillation plane. The energy resolution of the experiment will be about 15 per cent FWHM above 100 MeV.

2.4 Burst and Transient Source Experiment (BATSE)

BATSE is designed to study the unpredictable gamma-ray bursters and other transient events in terms of temporal styructure, spectra, and direction of incidence. The telescope is designed to continuously monitor the entire non-occulted sky. The instrument consists of eight wide field of view detection modules arranged on the GRO spacecraft in order to provide a maximum unobstructed viewing of the sky. The eight detection modules are each of identical design, as shown in Fig 4. The main detector element is a 50.8cm diameter, 1.3 cm thick NaI(T) scintillation crystal. (Fishman *et al* 1985). Each scintillator is optically coupled to three photomultiplier tubes and the data from each detector is processed in a central digital data processing unit. A plastic scintillator anticoincidence shield is placed at the front side of each module to reduce the effects of charged particles and a lead shield around the outside of the light box to reduce the amount of scattered radiaiton reaching the back side. A five inch diameter

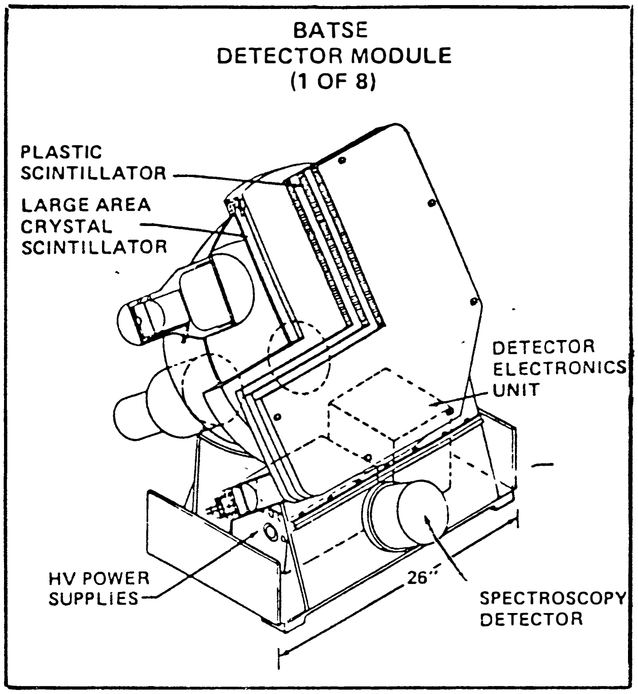


Fig 4. Burst and Transient Experiment BATSE Detector Module.

three inch thick NaL(T1) spectroscopy element is included in each module.

BASTE will operate over the photon energy range 20 keV to 10 MeV. The effective gamma-ray detection areas for each module are $> 1000\ cm^2$ for the main crystal. The spectral resolutions are typically 20 per cent FWHM and seven per cent FWHM respectively. Temporal fluctuation down to several microseconds may be detectable for sufficiently strong bursts as well as coarse spectral variations on timescales as short as 10 ms. The location of the bursts to within several degrees may be determined using the relative responses of the large area detectors. Clearly the large increase in size of the BATSE detectors over and above the necessarily small instruments on interplanetary spacecraft, will enable the detection of some hundreds of bursts per annum, thus enabling a better size spectrum and accurate spatial distribution of these events to be determined.

3 THE GAMMA-1 MISSION

The Gamma-1 telescope is a cooperative project between a number of Soviet and French organisations which was initiated, in the mid 1970's, as a follow up to the COS B and SAS II missions. Like GRO, but for different reasons, this programme has also suffered considerable delay in materialisation. The Gamma 1 telescope is mounted in a SOYUZ spacecraft and launch is anticipated in mid 1988 into a circular orbit at 400 km, inclined at 51 degees to the equator. The satellite vehicle will be a 3 axis stabilised system with a pointing accuracy better than 0.5 degrees

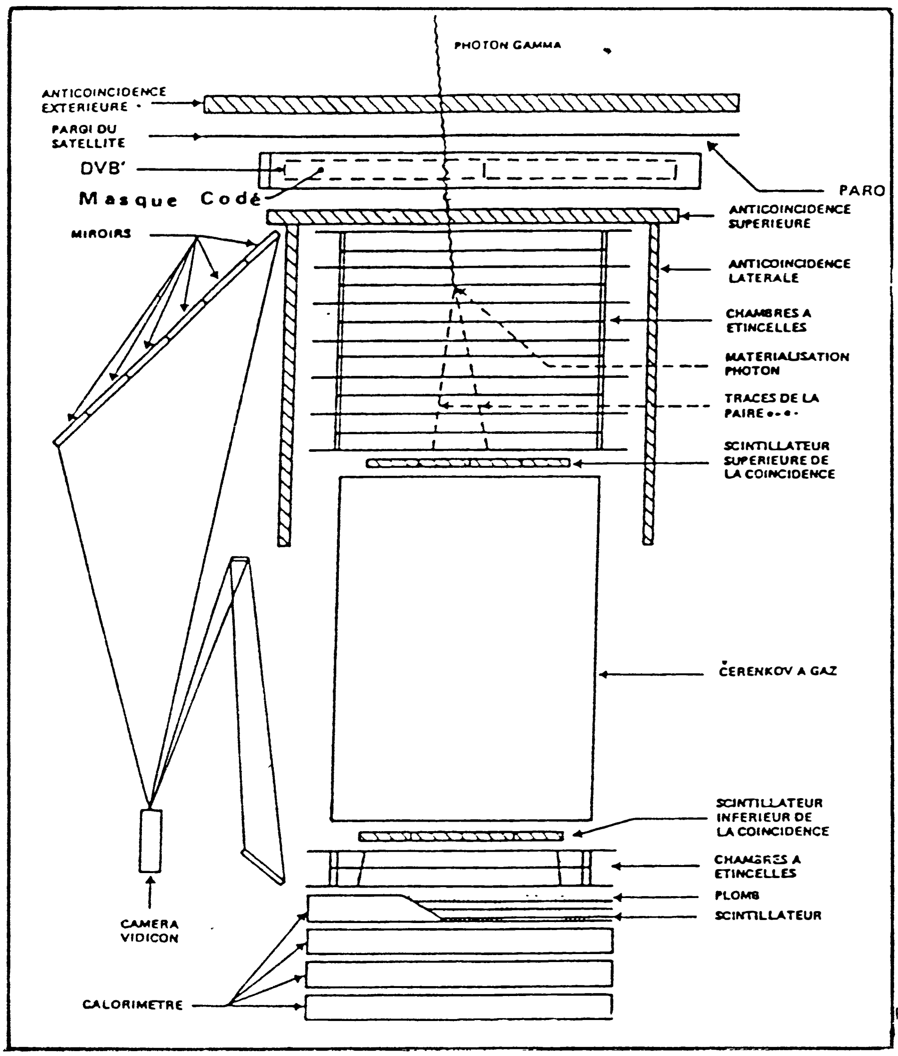


Fig 5 A schematic view of the Gamma 1 telescope

and knowledge of the pointing direction given to better than 5 arc min. Gamma-ray events will be timed to better than 2ms. The main scientific programme during the year lifetime is likely to concentrate on the study and identification of COS B sources.

A schematic view of the Gamma I instrument is shown in Fig 5 and the design is centred around a 50 × 50 cm 12 gap spark chamber with 3 cm gaps and a total converter thickness amounting to about 0.45 radiation lengths (Agrinier *et al*, 1986). The instrument is intended to be operated over the photon energy range 50 to 5000 MeV. Gamma-ray events are selected on the basis that it converts by pair production in the spark chamber and the electrons are subsequently registered in the two plastic scintillators and gas Cerenkov counter which define the event selection telescope. Downward moving electrons are selected from slower protons or upward moving particles by the combination of a time of flight analysis on the two scintillation counters and the direct response and velocity selection in the gas Cerenkov counter. The detection efficiency to on axis gamma-rays increases with photon energy to about 20 per cent at 200 MeV and subsequently flattens above this value. Both the spark chamber and the trigger unit are shielded from charged particles by anticoincidence scintillator counters placed on the four sides as well as the top of the system. A two gap spark chamber, placed beneath the lower counter of the scintillation telescope helps identify the forked tracks from $e^{\mp}$ pairs not visible in the upper chambers and serves to refine the positions of particle entry into the energy calorimeter placed at the bottom of the system. This latter device is 7.4 radiation lengths thick and is constructed from a stack of 24 scintillator counters and 24 lead plates designed to study the electromagnetic cascades which develop from the energetic electrons which leave the spark chamber/trigger telescope system. The spectral resolution of the telescope varies from about 70 per cent FWHM at 100 MeV to 40 per cent at 500 MeV.

At a later stage in the development programme of this telescope a coded aperture mask made from 10mm thick tungsten elements was incorporated into the system, which, on telecommand, can be introduced in the field of view 'above' the telescope. Thus observations are possible with and without the coded mask. Unfortunately the mask is rather close to the spark chamber and thus the full potential gain in angular resolution over and above that of a normal spark chamber cannot be achieved. The angular resolution thus varies from a few degrees FWHM without the mask to approximately 20 arc minutes with the coded mask in position. Note that the use of the mask offers the same angular resolution over the spectral range, whilst without the mask the angular resolving power degrades at the lower end of the operational range (as for the case of EGRET).

Table 2. Typical performance parameters of the GAMMA 1, SIGMA and GRASP telescopes.

Parameter	GAMMA 1	SIGMA	GRASP
Energy range (MeV)	50-50000	0.03-2	0.02-100
Energy Res. E/ΔE	3	10	1000
Max.effective area $cm^2 \times$ efficiency	500	500	3000
Solid angle aperture	100 sq. deg.	40 sq. deg.	50 sq. deg.
Angular res.FWHM	20' (with mask)	7'	6'
3σ sensitivity mCrab in 10^6s	100	5 at 100 keV 100 at 1MeV	<3 over entire range
3σ line sens. ph $cm^{-2}s^{-1}$	–	$1.6\,10^{-4}$	$3\,10^{-6}$
Temporal res. ms	1	1	0.1
Polarimetry	Yes	No	Yes

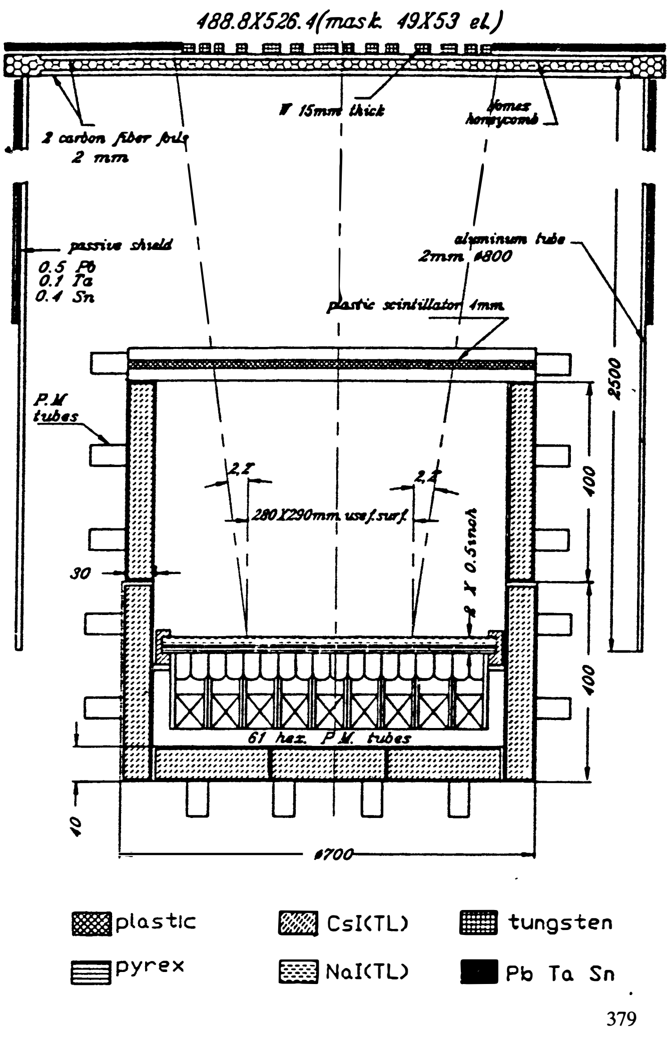
4. THE SIGMA MISSION

SIGMA is another Franco-Soviet mission planned for launch in the late 1980's. The telescope will be placed into a highly eccentric orbit with a perigee of 2000 km, and apogee of 200,000 km, and period of 4.5 days. This orbit will allow uninterrupted observation of the sky, above the radiation belts, for periods of up to four days. The principal objectives of this mission are to image the hard X-low energy gammaray sky (0.03 to 2 MeV) with arc minute precision. This instrument was designed around the coded aperture mask principle and makes full use of its potential in conjunction with a scintillation quality detector plane. The major scientific objectives will be the localisation and study of both galactic and extragalactic sky regions in the spectral range immediately adjacent to the 'classic' X-ray band. (1-10 keV).

The position sensitive detector plane is constructed from a classic Anger camera device which is buried in an extensive shielding system. (Mandrou 1984). A schematic view is shown in Fig 6. The Anger camera is viewed by 61 hexagonal photomultiplier tubes and locates interacting photons with a positional resolution of 5 mm FWHM at 122 keV over a sensitive detection area of 825 cm^2.

The active anticoincidence shield is made from C_sI(T) elements and surrounds the detection plane leaving a forward aperture in the direction of the mask. A thin plastic shield closes the top of the veto 'well' and effectively improves the rejection of background noise derived from charged particles which enter from this forward entrance window. A graded shield arrangement closes the remaining forward aperture (apart from that subtended by the

Fig. 6. A schematic view of the SIGMA telescope.



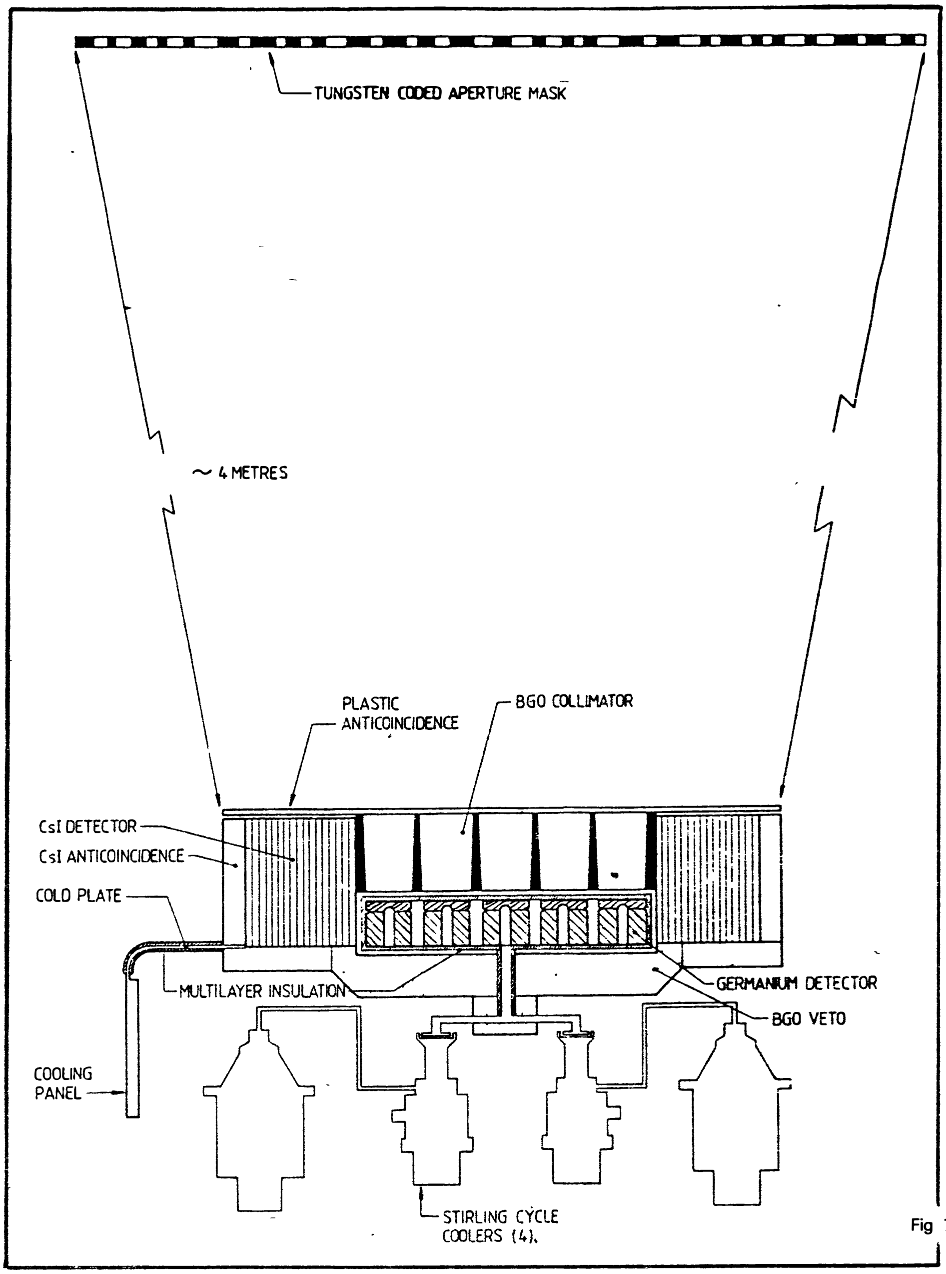


Fig 7. A schematic view of the GRASP telescope.

coded aperture mask) and thus further reduces the cosmic diffuse hard X-ray flux which can reach the detection plane and generate unwanted background noise.

The coded aperture mask is placed 2.5 m above the detection plane and is constructed from 1.5 cm thick tungsten elements. The mask pattern is based on a 57 × 61 element Uniformly Redundant Array with a basic mask pattern of 29 × 30 elements. The positional resolution of the Anger camera plane is typically 5 mm FWHM and with the mask at 2.5 m yields a resolving power of about seven arc min FWHM for a point source.

The 1.25 cm thick Anger camera ensures that the telescope efficiently converts hard X-rays up to about 300 keV. Above this energy the detection efficiency decreases significantly with increasing photon energy. The spectral resolution is typical of scintillation counter spectroscopy and ranges from about 25 per cent FWHM at 200 keV to seven per cent at 1 MeV.

5. GAMMA-RAY ASTRONOMY WITH SPECTROSCOPY AND POSITIONING – GRASP

The GRASP mission is a third generation gamma-ray telescope and is designed to operate as a high quality spectral imager in the mid 1990's, when, following the GRO, SIGMA and GAMMA 1 missions, there will be a requirement for an instrument with such a capability to maintain the momentum of advance in gamma-ray astronomy. The GRASP telescope, which is currently under study as a prospective ESA mission, will be capable of locating point sources of gamma-rays over a wide photon energy range (20 keV to 100 MeV) with a precision of the order of 1 arc minute, whilst making a fine spectral analysis ($E/\Delta E \sim 1000$) of any gamma-ray line features in their emission spectra.

The telescope (Bignami *et al* 1987) is designed around the combination of a coded aperture mask and a position sensitive gamma-ray detection plane. This component of the telescope is constructed from a number of CsI(T1) scintillators and germanium solid state detectors arranged into a continuous position sensitive matrix. The array of position sensitive CsI scintillators also provides a highly efficient active shield for the solid state detectors. A schematic view of the GRASP telescope is shown in Fig 7. The Germanium detectors are cooled to approximately 100 degrees K by Stirling cycle coolers to ensure that

these elements can be operated for an extended period of time (three years) in space.

As with all modern gamma-ray telescopes great care has been taken to ensure the efficient selection of genuine cosmic gamma-ray events from the unwanted background noise. In this context both the Germanium and CsI detectors have the capability to identify and measure multiple site energy deposits within their sensitive volumes. Above a few hundred keV, gamma-rays are observed by multiple, spatially separated, interactions which relate to Compton scatters around 1 MeV and electromagnetic cascades at higher energies. In contrast the primary detector background component at these energies in a heavily shielded system is dominated by neutron scattering and β-decays of radionuclides. The energy deposit of the β-particles is primarily located in a single site. Thus GRASP has the capability to distinguish between genuine gamma-ray photons and background, hence improving the sensitivity of the instrument. Furthermore, the 3-D gamma-ray detection capability will enable a verification that the candidate gamma-ray did come from the general direction of the source under study by means of a kinematical analysis of the Compton and electromagnetic processes. This feature can enhance the signal to noise of gamma-ray telescopes in a similar manner to that achieved at other wavelengths by the use of focussing optics. As an additional bonus, the kinematical analysis renders GRASP a sensitive polarimeter.

The Germanium/CsI combination imager plane is assembled inside an active veto system and provides a highly efficient (100 per cent over the entire range 30 keV to greater than 100 MeV) position sensitive gamma-ray detection plane. The imager matrix is formed from discrete pixels of typical dimension 9 mm.

The coded aperature mask will be placed 4.5 m above the detectors and constructed from 2 cm thick tungsten elements. The pattern is based upon a hexagonally celled uniformly redundant array which periodically replaces mask patterns by anti-mask patterns thus producing a 'chopped' signal within the detection pixels as the mask is rotated.

6. SUMMARY

The missions described above outline the technical capabilities of the space-borne gamma-ray telescopes expected to be operational in the period leading up to the end of the century. If all of these missions are successful then a clear progression of measurement capacity can be identified which should lift gamma-ray astronomy from the initial exploratory phase to a fully fledged branch of observational astronomy which is comparable to that currently enjoyed at other wavelengths. By the mid 1990's we may expect the following progress to have been made: at higher energies ($E_\gamma > 100$ MeV) the GAMMA 1 mission will have made images of a limited number of regions of the sky, probably the strongest COS-B source regions; SIGMA will have made images of the sky in the sub-MeV photon band with moderate spectral resolution; the GRO mission, with its excellent sensitivity in both the low energy and high energy ranges will have detected a significant number of sources with scintillation quality spectral resolution. However, the limited angular resolution of the GRO telescopes will inevitably mean that a considerable level of source confusion will exist with corresponding problems of source identification. The GRASP instrument will follow and maintain the momentum of advance in gamma-ray astronomy by exploiting its high sensitivity coupled with the ability to unravel both the source identification problems and fine spectral details.

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