European Photon Imaging Camera (EPIC) for X-ray Astronomy

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ABSTRACT

The European Space Agency has selected, in early 1989, the final payload for its "Cornerstone" mission in X-Ray astronomy with multiple mirrors (XMM), to be flown in the late nineties in the context of the "Horizon 2000" long term science plan. EPIC, a collaboration of 13 Institutes in four European countries, represents the main instrument of the mission, to include three CCD arrays in the focal planes of the three telescopes of the spacecraft. They will be dedicated to source imaging, photometry, spectroscopy and timing, and will serve a worldwide community in this Observatory-class mission, built to last many years, possibly a decade, in orbit.

The goals of EPIC as a tool for post-AXAF, advanced X-Ray astronomy include high-throughput source detection, imaging and photometry at the 2×10^{-15} erg/cm^{2}sec peak sensitivity level (for 10^5sec observing time) in the X-ray interval .1 to 10 KeV, thanks to a peak effective area of 3,000 cm^2. The source location accuracy will depend on the telescope Point Spread Function, better than 30", but the CCD pixels size will in any case allow ample oversampling of the source image. The spectral resolution will range from 50 eV at 1 KeV to 150 eV at 7 KeV, or possibly better, following chip optimization. Source photon timing will be possible at 16 microsec accuracy in the high resolution mode of the pn device, where as the "normal" full frame mode will yield images every 50 sec.

INTRODUCTION

The European Photon Imaging Camera (EPIC) has been selected in 1989 as the instrument devoted to performing imaging and spectroscopy of the X-ray sky with the ESA XMM mission. Conceived as a "cornerstone" of the Agency's "Horizon 2000" strategic science plan, XMM is due to fly in the 1998 time frame as an astronomical facility characterized by an X-ray focusing optics of unprecedented throughput in the domain ~0.1 to 10 Kev and an angular resolution better than 30" HEW.

This instrument will be realized by a large collaboration of thirteen institutes in four European countries and the related Space Agencies, ASI (Italy), CNES (France), SERC (U.K.), BMFT (German), will provide the necessary funding and support.

1.THE EPIC CAPABILITIES

The EPIC instrument consists of three similar focal plane cameras, each camera to be mounted at the focus of the three telescope modules which comprise the full XMM optics.

The detecting elements are charge coupled devices (CCD), with each camera employing an array of CCDs so as to give full coverage of the XMM field of view. The exact choice of CCD to be used in the EPIC will be made at a later date, subject to the results of parallel development programs being carried out by three of the institutes within the instrument consortium.

The main design goal for XMM was to achieve high-throughput, particularly at energies above several KeV, with spatial resolution sufficient to allow detailed spectroscopic studies of faint sources. By using the combined grasp of the three XMM telescopes, the EPIC successfully achieves this goal. We note in particular that, given the likely telescope configuration in which the effective collecting area of two telescope module is reduced due to the inclusion of gratings in the light path, then approximately half of the EPIC sensitivity derives from the telescope with the clear field of view. However, with a suitable choice of CCD for each of the telescopes we can optimize the range of scientific return from the total instrument complement.

In the following sections we outline the characteristics of the CCD devices currently being developed in the consortium institutes, discuss the performance of the baseline EPIC instrument when coupled with the telescope module design currently chosen and identify some of the key scientific areas which this instrument combination will be able to address.

CCD Characteristics

As noted above there are three different CCDs under development at consortium institutes. The CCDs produced by Thomson and EEV utilize frame transfer MOS technology(1,2,3,4,5,6,7,8) and are under study in France and the UK respectively, whereas novel pn-devices are being developed in West Germany(9,10,11,12,13).

Although the three devices under consideration are broadly similar in terms of their use as X-ray detectors, their characteristics do differ in detail. In summary the characteristics of the CCDs under consideration are as follows. The limiting spatial resolution of the devices ranges from 20 microns (MOS CCDs) to 150 microns (pn-CCDs). The peak quantum efficiency exceeds 90% as illustrated in Figure 1, which shows the quantum efficiency as a function of energy for both the MOS and pn devices. Note that an efficiency better than 10% is achieved over a wide energy pass-band. The spectral resolution ranges from 50 eV at 1 KeV to 150 eV at 7 KeV. The effective time resolution and field-of-view will depend upon the operational mode. In the normal operating mode, which will be appropriate for faint source studies, full frame imaging will be provided with a time resolution of 50 s, whereas a high time resolution mode (in the case of the pn device) will allow timing down to 16 microsecond over a restricted field-of-view.

Scientific Performance

For the purposes of evaluating the potential scientific performance of the EPIC, we have assumed a baseline configuration of 2 frame transfer CCDs and 1 pn CCD, with the pn CCD and 1 frame transfer CCD having grasps reduced by a factor of 2 below the nominal full module grasp due to the inclusion of gratings in the field-of-view.

Spatial Resolution

The minimum design goal for the XMM optics requires an angular resolution of HEW 30". Given the 7.5m focal length of the XMM telescopes, this corresponds to a linear dimension of 1 mm. Clearly the intrinsic spatial resolution of the CCDs far exceeds the minimum requirement even if an enhanced optical performance of, say, 10" (HEW) is achieved. Clusters of galaxies will be well resolved at all redshifts whilst the cooling flow component in such objects will be resolved to redshifts of about unity. Individual galaxies out to distance of 300 Mpc will also be resolved. (We note that a 10" resolution would imply that both cluster cooling flows and large galaxies could be imaged to very high redshifts). By using an array of CCDs in each EPIC camera the full 30' x 30' field-of-view available from the telescope optics can be covered. This field-of-view is sufficiently large to encompass all but the largest supernova remnants and the nearest rich clusters of galaxies.

Energy Band-Pass and Faint Source Sensitivity

Figure 2 illustrates the resultant effective area for the EPIC instrument in the three telescope configuration. The effective area is 3000 cm^2 at 1 KeV and about 2000 cm^2 at 6 KeV; the energy band-pass is 0.2 - 10 KeV (for which the effective area > 100 cm^2).
One of the key measures of the instrument sensitivity is the time required to detect sources of different strengths. We have assumed a background consisting of 3 components: (i) the diffuse cosmic X-ray background, (ii) the (soft) galactic X-ray background and (iii) a minimum ionising particle background of 1.6 cm^{-2} s^{-1}. A background rejection efficiency of 99% has been assumed, which is in good agreement with laboratory data for the EEV MOS CCD. (For the pn CCD

it has been measured that use of an energy veto can lead to a better rejection efficiency). The energy dependence of the unrejected events has been estimated with the assumption that the soft electron component is fully contained by magnetic diverters at the mirror module. Curves showing the time required to detect sources in 3 different energy bands as a function of the integrated source flux are shown in Figure 3. Given the proposed XMM orbit, a deep exposure might be typically between 2 to 6 x 10000 s, in which time a source with a 0.5 - 5 KeV flux of about $2x10^{-15}$ erg cm^{-2} s^{-1} can be detected (3 module configuration). This is 10 times fainter than the Einstein deep survey limit. At the level of the Einstein deep survey, there are 10-20 sources/sq deg. This converts, assuming an Euclidean extrapolation to the X-ray source counts, to 22-45 XMM (30" x 30") beams per source at the fainter flux level noted above. A 40 beams/source criterion is often adopted as a measure of the source confusion limit, clearly the EPIC will just reach this limit in deep exposures. Typically over 100 faint sources will be detected over the full field-of-view in such observations. If the source counts maintain a Euclidean slope as assumed above then, at the XMM confusion limit, roughly 40 percent of the extragalactic diffuse X-ray background will have been directly imaged.

Spectral Resolution and Sensitivity

The measured spectral resolving power of the CCD device ranges from about 10 (50 eV) at 0.5 Kev to 50 (130 eV) at 6.7 KeV, in good agreement with that predicted theoretically. Such spectral resolution will be sufficient to resolve He- and H-like lines of the elements which dominate the emission line spectrum in the pass-band of the instrument, and to measure velocities to an accuracy of order 500 km/s and resolve velocity structures with widths greater than about 3000 km/s. This capability will be of importance in measuring the redshift of sources independent of their optical identification and also in studies of sources in which high velocity material may be present, for example within an accretion disk or an anisotropic outflow. The sensitivity of the EPIC for the detection of lines depends on the line strength, the source continuum level and the observation time. In Figures 4a and 4b we show for illustration the minimum detectable line strength as a function of the surrounding continuum levels for O VII and Fe XXV.

Timing Capability

As noted above in the normal operating mode, which will provide full frame imaging, the time resolution of the EPIC will be 50s. By trading imaging information for timing, the MOS device can reach approximately 2 msec. A high time resolution mode will, however, extend the capability down to 16 microsec (with the pn device). Furthermore, the deep orbit of XMM will allow uninterrupted observations of up to 6x10000 s, which following the success of

EXOSAT, has been recognized as crucial for timing and variability studies of many categories of X-ray source (e.g. active galaxies).

Summary of the Scientific Rationale

The EPIC, in conjunction with the XMM optics, will provide a facility with a superb sensitivity, a wide energy-band pass, excellent energy resolution, 30" imaging and a useful timing capability. These characteristics were identified in the XMM mission science report as constituting a world-class observatory mission fully complementary to the AXAF mission, concentrated on high angular resolution. In particular, the 130 eV spectral resolution at FeXXV (6.7 KeV),now obtained in tests, coupled with an effective area of about 2000 cm^2 presents an unsurpassed spectroscopic capability. Similarly, a deep exposure sensitivity matched to the confusion limit and equal to a tenth of the Einstein deep survey limit represents a formidable capability for faint source detection and for imaging low-surface brightness structures. Given this performance, the range and scope of the astrophysics that can be addressed using the EPIC is vast. Programs which will figure very prominently in the early phases of the mission include the question of the origin of the X-ray background, studied through both source count and fluctuation measurements, the spectral imaging of clusters of galaxies, normal galaxies and galactic supernova remnants, detailed spectroscopic and timing studies of active galaxies and also of X-ray binary systems within the local group, and finally studies of various phenomena relating to stellar coronae, radio pulsars and the interstellar medium.

2. INSTRUMENT SYSTEM CONCEPT

The three Focal Plane Imagers of the EPIC instrument (one for each telescope) consist of five modules,

a) Focal Plane Camera (FPC)
b) Detector Analogue Electronics (DAE)
c) Detector Controller Electronics (DCE)
d) Instrument Data Handling System (IDHS)
e) Power Conditioning Unit (PCU)

The FPC houses the CCD array inside a vacuum enclosure with an associated cooling system to enable the array to operate at the required temperature. An aluminized lexan filter is located in front of the array to suppress optical and UV flux. This filter also limits the instrument response below 0.2 KeV, through increased x-ray absorption in the filter below this wavelength. The possibility of a filter wheel is currently considered for operational flexibility. Passive cooling is provided by a radiator viewing deep space and coupled to the CCD via a thermally conducting link. Regulation of the CCD temperature (+/-1°C) is via an electronic controller in the DAE. CCD clock drives, signal processing and digitization are also incorporated in the DAE module. The control of the CCD cameras, governing timing and operating modes of the instrument, detection of X-ray events and background event recognition, reside in the DCE. Commanding, event processing and digital data management functions are incorporated in the IDHS. A radiation monitor sensor (RMS) located near the CCD detector provides dedicated signals to alert the FPI to high levels of background radiation that might be encountered during satellite passages through the radiation belts or solar flares. Signals from the 3 RMS are conditioned by a common Radiation Monitor Electronics (RME) which interfaces directly to the spacecraft power and OBDH buses. Switching control of radiation sensitive modules in the FPIs is via the the spacecraft OBDH. The overall concept of the EPIC is illustrated by the system block diagram, Figure 5.

Each FPI has its independent electronics system, with a separate interface to the spacecraft. These electronic systems control the FPI, and transform the signals from the CCD's to the standard OBDH telemetry format. The front-end electronics and controller for the MOS-CCD and the pn-CCD are different, but will have identical interfaces to the IDHS, which is independent of the type of detector, except for some software differences.

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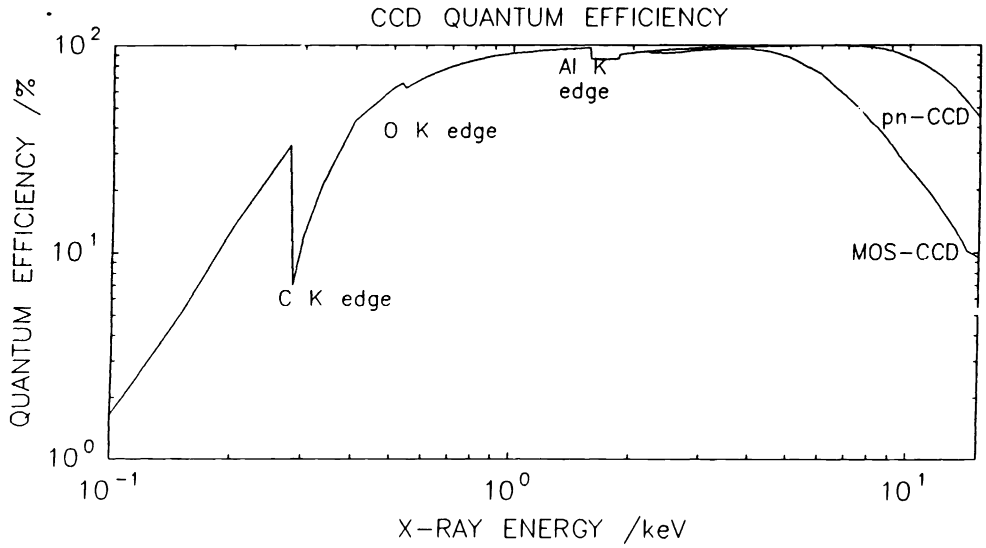

Figure 1-The quantum efficiency versus energy for the MOS and p-n CCDs (with a 1000 A Al plus 2000 A Lexan filter)

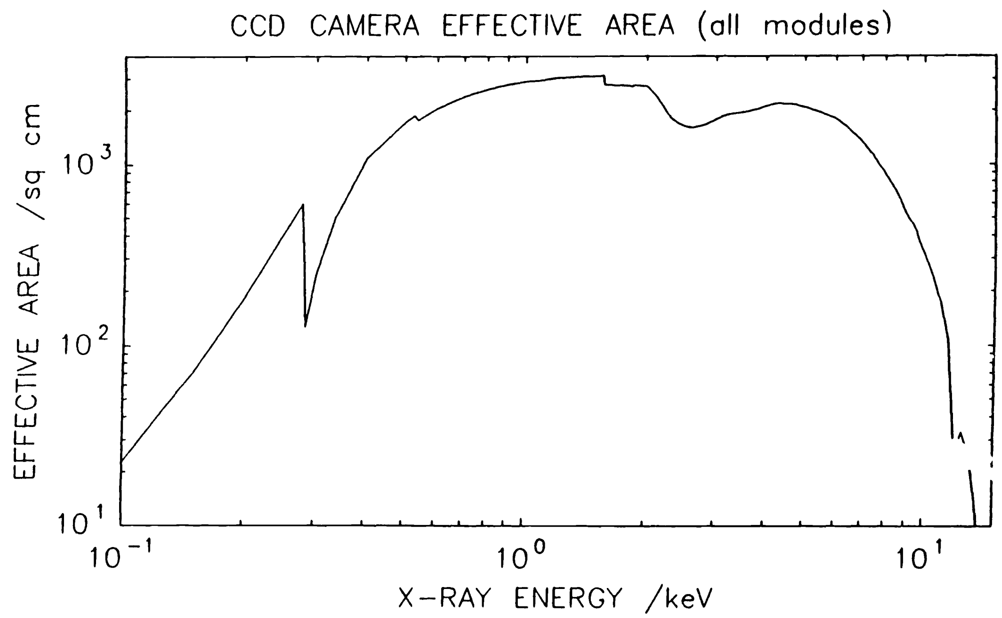

Figure 2-The effective area as a function of energy for the EPIC. A three module configuration is assumed.

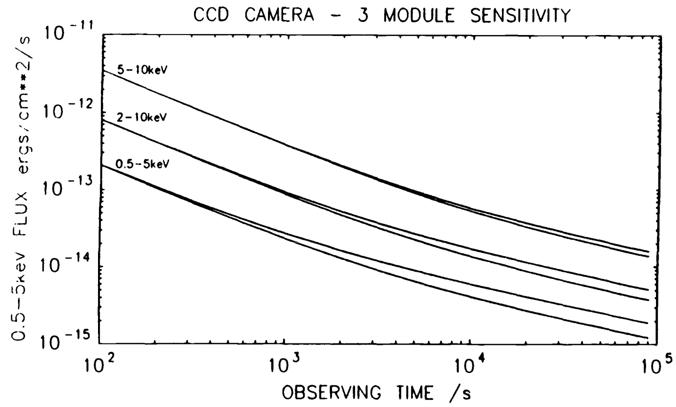

Figure 3-Point source sensitivity of the EPIC versus integration time in three energy bands.

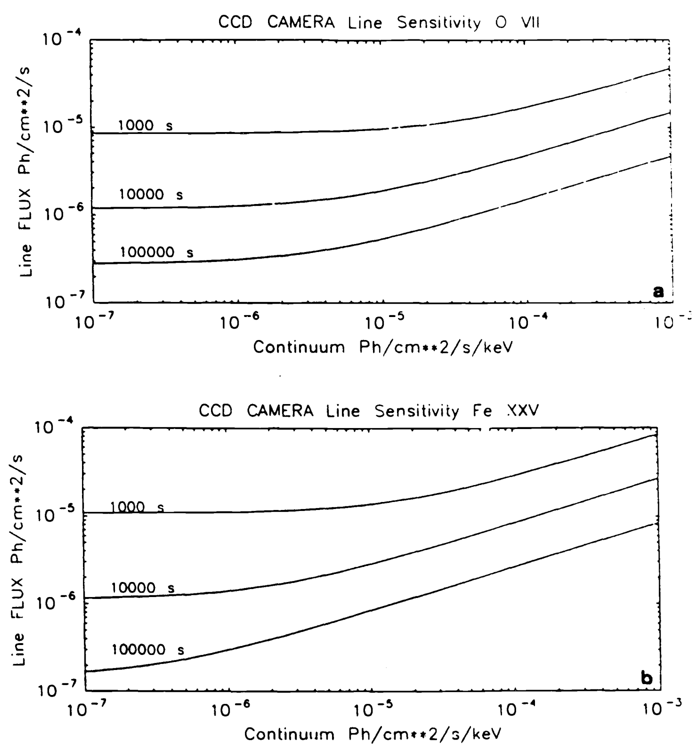

Figure 4-Spectral line sensitivity of the EPIC as a function of the continuum level for three integration times (a) at 600 eV (O VII) (b) at 6.7 KeV (FeXXV).

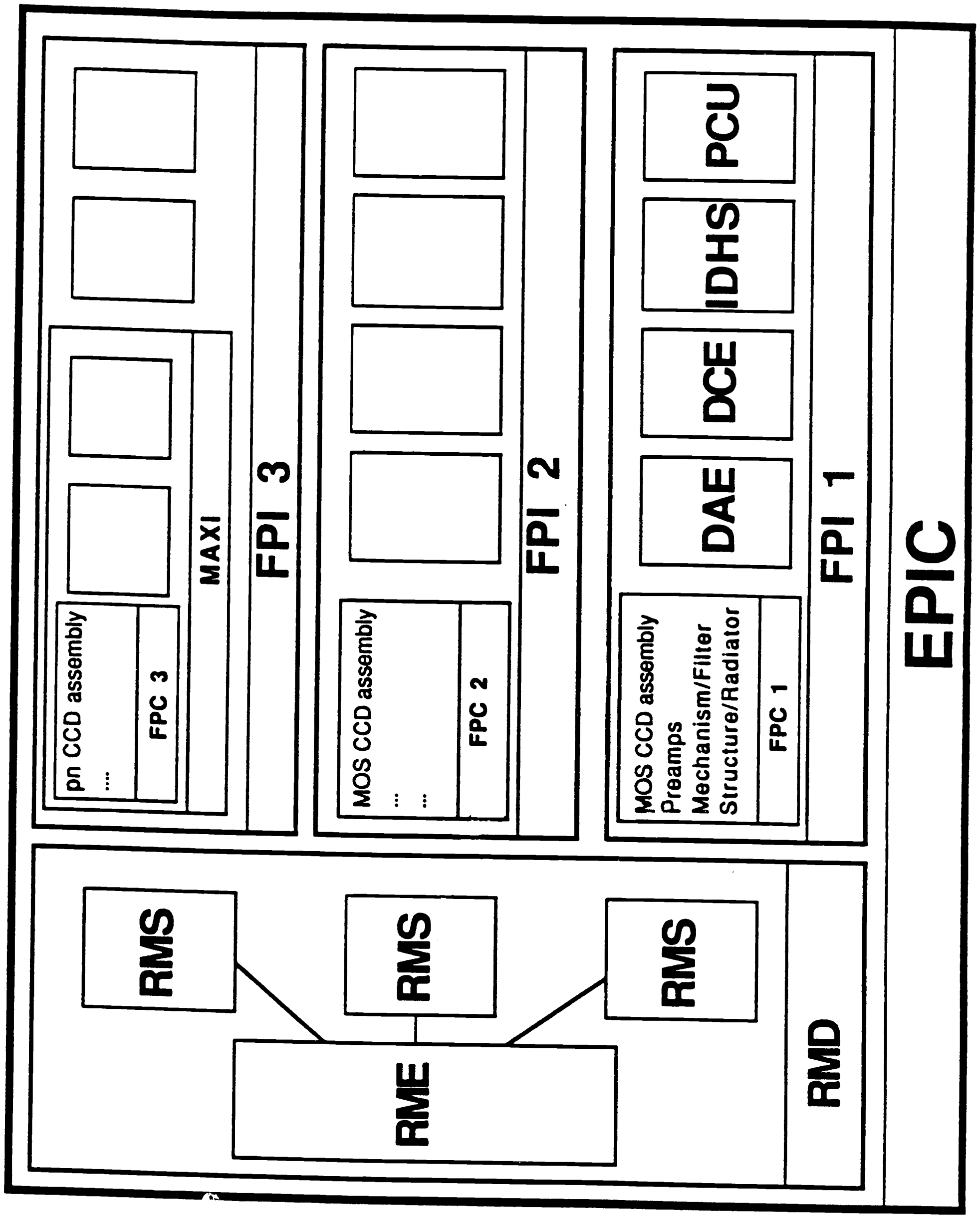

Figure 5- The EPIC system block diagram (see text).