Part I

Talks

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Section A

Space Missions and Observations

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The Next Generation of High-energy Astrophysics Observatories

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Abstract. The sky will soon be populated with a fleet of new X- and gamma-ray satellites with extraordinary capabilities. This paper is meant to introduce these new missions, *Chandra*, XMM, and Astro-E, which will provide a large fraction of our high energy "space observatory" functionality for the next decade.

1. Introduction

The universe is fashionably lean this year. Current estimates (from SN Ia studies, Perlmutter et al. 1999) suggest a flat universe (i.e., a total density equal to the critical density of $10^{-29}\,\mathrm{g\,cm^{-3}}$), of which the mass component (both baryonic and dark) is only about one-quarter of the total. But even if the total critical density was in baryons (in violent conflict with all of the currently fashionable conclusions about the contributions of dark matter and the cosmological constant), the universe, out to the time of the recombination of the primordial plasma, would still be Compton-transparent for X-rays and low-energy gamma-rays, on average. We could, therefore, have anticipated the extent to which X-ray astronomy would provide undistorted images of the high-energy universe well in advance of our ability to get above the atmosphere to actually discover them in the early 1960s.

X-ray astronomy has come a long way in the past four decades. X-ray astronomical imaging has proceeded from reconstructions made from single "pixel" measurements with mechanically collimated detectors having fields-of-view at the level of degrees, to focusing optics with linear point-spread functions of 1/4 arc-sec. Spectroscopic capability (with sufficient sensitivity to be useful) has similarly proceeded from a resolving power (the energy of the measured photon divided by the full-width-half-maximum energy resolution with which that energy can be measured) of unity to more than a thousand. At the same time, the effective apertures that we can apply to such measurements are approaching a square-meter.

The next six months will produce three new X-ray astronomy observatories of unprecedented sensitivity. *Chandra*, scheduled to be launched soon after this meeting, will be the venue of choice for the sharpest imagery. XMM, scheduled to be launched in December of 1999, will have the largest aperture. Astro-E, planned for a relaunch in 2004–2005, will have the best spectral sensitivity.

The scientific potential of this fleet of observatories is enormous. There are many important studies that can be anticipated, and many discoveries that

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cannot. In lieu of reviewing the obvious and/or speculating about the potential surprises, I have attempted to provide enough quantitative information about each observatory to allow the reader to estimate the extent to which his/her favorite idea might be testable.

2. Chandra and X-ray Imaging

During most of the first two decades of X-ray astronomical research, most source identifications were made with mechanically collimated proportional counters, with typical fields-of-view of one square-degree or more. Some sources were identified with objects that were distinguished in other energy bands (like the Crab nebula and 3C273), and others with no such obvious counterparts were given X-ray designations like Sco X-1 (the first discovered, and brightest, nonsolar X-ray source, in the constellation Scorpius).

In the early days of few-minute exposures from rocket flights, there were a few very imaginative attempts to produce much finer spatial resolution for the very brightest X-ray sources. One of these was the rotating modulation collimator investigation that was able to locate Sco X-1 well enough to correctly identify its stellar counterpart (Clark et al. 1965). Another was the utilization of a lunar eclipse to locate the neutron star pulsar in the Crab nebula (Bowyer et al. 1964). In fact, the anticipated utilization of lunar eclipses to precisely locate X-ray sources (in one dimension) was the rationale for placing the European *Exosat* mission in a highly elliptical orbit.

Delays in the launch of *Exosat* rendered its lunar occultation capability irrelevant when the *Einstein Observatory* (HEAO-2, the second in the series of *High Energy Astronomical Observatories*) was launched approximately twenty years ago. This followed a series of small X-ray satellites devoted to X-ray astronomy that was begun about ten years previous to the launch of *Einstein* with *Uhuru* (SAS-1, the first in the series of *Small Astronomical Satellites*, and the first NASA satellite devoted to X-ray astronomical research). The *Einstein Observatory* revolutionized X-ray astronomy, allowing for true X-ray images with spatial resolution of a few arc-seconds over a field-of-view of tens of arc-minutes, utilizing small, imaging focal plane detectors with a fraction of the internal background of mechanically collimated proportional counters of the size of the aperture. Its four-nested-element telescope had a geometric area of a few hundred square-centimeters, but a high-energy cutoff of only about 4 keV. Its primary purpose was to do pointed observations of the not-much-more-than 1000 sources that were catalogued (but with relatively few identifications) at the time of its launch. There were also spectroscopic instruments onboard *Einstein*, but it is fair to say that the biggest impact of the mission came from its two imaging detectors: a proportional counter that covered the total field-of-view and energy range of the telescope with high efficiency but with spatial accuracy somewhat cruder than that of the telescope, and a high resolution camera with no energy resolution capable of oversampling the telescope's on-axis spatial resolution of about 4 arc-sec.

The German-led ROSAT mission, launched about ten years after the *Einstein Observatory* with an updated complement of its imaging detectors, was primarily designed to conduct an all-sky survey with spatial resolution similar to that of the *Einstein Observatory*. Its telescope had similar geometric area (approximately 400 cm^2) and slightly better spatial resolution than did *Einstein*, but it had an even lower high-energy cutoff (about 2 keV). After the completion of its sky survey (which resulted in a catalog of about 80,000 sources), it spent the remainder of its lifetime performing pointed observations with its two imaging cameras.

Chandra, to be launched some ten years after ROSAT, carries on the tradition of imaging X-ray observations, but with some significant increases in capability. Named to honor Subramanyan Chandrasekhar, it had been known throughout its long development phase as AXAF (the *Advanced X-ray Astrophysics Facility*). Its spatial resolution in one dimension is more than an order of magnitude better than that of its predecessors (so that its imagery is more than two orders of magnitude sharper). It has a single four-element grazing-incidence telescope with a geometric area in excess of 1000 cm^2, and a long-enough focal length (10 m) to still have an area in excess of 10 cm^2 at 10 keV. It has two imagers: a high-resolution camera that oversamples the telescope spatial resolution over its entire 30 arc-minute-diameter field-of-view, and an array of CCDs that provide simultaneous energy resolution at the 100 eV (FWHM) level over about one-quarter of that field-of-view. Higher spectroscopic resolving power can be obtained via the utilization of objective transmission gratings. There is only one optical path, so that only one of the four basically different observational modes (i.e., high resolution camera or CCDs in the focal plane, with or without transmission gratings in the optical path) can be utilized at any time.

Additional details and updated information about *Chandra* can be found at `http://asc.harvard.edu`.

At the time of submission of this manuscript, *Chandra* has been successfully launched with all instruments initially operating in complete accordance with their preflight specifications. Shortly after the commissioning observations, however, it was noticed that the charge transfer efficiency (and hence the energy resolution) of most of the CCD detectors (those that are "front-side illuminated") was worsening rapidly. Currently, the resolution capability of these CCDs is similar to that which can be obtained with proportional counters (see next section). The problem has been identified as arising from large doses of few-hundred keV protons deep in the radiation belts, and future degradation can be minimized by altering the geometry to allow shielding of the CCD detectors during such exposures. Of the total of ten CCDs, the two that are "back-side illuminated" have not had their energy resolution compromised by the radiation damage, but each of these cannot cover as much as 1/10 of the telescope field-of-view. Whereas the back-side illuminated CCDs can still provide what might be characterized as X-ray color images (with an energy resolving power at the Fe-K lines of about 50), the imaging observations that will be made with either the front-side illuminated CCDs or the high resolution camera might be better characterized as black-and-white (with resolving power < 5 at Fe-K), although with spatial resolution that is uncompromised with respect to pre-launch expectations.

3. Astro-E and X-ray Spectroscopy

The proportional counters used for early X-ray astronomical measurements had resolving powers of no more than two or three. Nevertheless, the very detection of X-rays was a spectroscopic measurement in the sense that it implied source plasmas at effective temperatures in excess of millions of degrees.

The first generation of X-ray sources, with apparent X-ray magnitudes (in physical rather than astronomical units) of about $10^{-9}\,\mathrm{erg/(cm^2\,s)}$ for the ten brightest, could provide hundreds of detected photons to mechanically-collimated proportional counters in few-minute sounding rocket observations. First-generation "spectroscopy" generally characterized these sources as being consistent with power laws or bremsstrahlung continua (or both) over a dynamic range similar to the resolving power of these detectors. This was actually a pretty good match, in the sense that each of the few independent energy bins accumulated enough counts for about 10% statistical precision, which was not much worse than the detector calibration.

The advent of satellite observations provided the opportunity for deeper observations. This meant not only that the detectors had to be better calibrated, but that better resolving power could be usefully applied. Several groups worked hard to provide proportional counters with the limiting resolving power of gas amplification systems of about 6 at 6 keV. This increased resolving power allowed for the unambiguous detection of Fe-K emission in sources with prominent (large equivalent continuum width) Fe-K features like Cas A (Serlemitsos et al. 1973), but careful calibration was essential since, in general, both line features and continuum gradients had to be "detected" via the residuals from the inconsistency of data with model spectra.

The *Einstein Observatory* provided breakthroughs in spectroscopy as well as imaging. Dispersive grating and crystal spectrometers, which had been used in rocket flights to measure the X-ray spectra of huge solar flare fluxes, could not easily be made with large enough effective geometric areas or reflection efficiencies in early satellites to be useful for measuring nonsolar X-rays. Coupling the dispersive gratings/crystals as objectives with the telescope provided the opportunity for a large area with small focal plane detectors. The gratings were limited by the fact that the spectra were dispersed on the images of (typically) extended sources, and the crystals were limited by the fact that the whole spectrum could not be dispersed simultaneously, but both instruments provided some investigations with dispersed X-ray spectra at a resolving power far exceeding what was possible at that time with nondispersive detectors.

The *Einstein Observatory* also included a new nondispersive spectrometer that provided somewhat more general capability at a new level of sensitivity. The *Einstein* "solid state spectrometer" was a cryogenically cooled (to about 120 K), non-imaging silicon detector with a resolving power of almost 20 at the K lines of Si and S (this would have been a resolving power of approximately 40 at the K lines of Fe, but Fe-K energies were above the high-energy cutoff of the telescope).

The Japanese-led ASCA mission (the name is both that of a fabulous mythic Japanese bird and the acronym for *Advanced Satellite for Cosmology and Astrophysics*; it was called *Astro-D* prior to its launch) carried the first CCD array, which provided true imaging capability with spectroscopic resolving power corresponding to that of the *Einstein* solid state spectrometer. ASCA had telescopes with sensitivity out to 10 keV, so that the Fe-K lines could be investigated. All three of the new missions—*Chandra*, Astro-E, and XMM—each have imaging arrays of CCDs, with effective areas (at 1.5 keV) of about 500, 1600, and 2500 cm^2, respectively. *Chandra* and XMM also have grating spectrometers, which utilize their imaging detectors to obtain resolving powers approaching 1000 at energies less than 1 keV (but < 100 at the Fe-K lines).

The totally new spectroscopic capability of Astro-E is the "quantum microcalorimeter." Operating at a temperature of less than 100 mK, the detector "noise" associated with the exchange of phonons between the X-ray absorber and the cold sink can be of the order of 1 eV. This instrument was originally chosen to be part of the complement for *Chandra* (Holt 1987). Practical imaging arrays of 32 detectors have been made for Astro-E with the total system "noise" being such that the energy resolution of each of the pixels is not much more than 10 eV, so that the resolving power at Fe-K is > 500.

The microcalorimeter operates at the focus of a light-weight X-ray "foil" telescope constructed to maximize throughput over resolution. In contrast to the sub-arc-second imaging of *Chandra*, Astro-E operates with arc-minute spatial resolution. The Astro-E mission contains four similar additional telescopes, with CCD arrays similar to those of *Chandra* at their foci, that operate simultaneously with the microcalorimeter. Therefore, Astro-E can simultaneously apply a total of about 2000 cm^2 (at 1.5 keV) of effective area to the X-ray sky with arc-minute spatial resolution, over virtually the same energy range as *Chandra*.

Such high resolving power makes the microcalorimeter competitive with dispersive techniques, but with the distinct advantages of high efficiency, simultaneous response over the whole available energy range, and no dispersion of the photons in the focal plane that can be confused with source extent. This is especially important in the case of line emission from spatially extended (i.e., larger than about 30 arc-sec) objects that are rich in line emission, such as supernova remnants and clusters of galaxies.

The Astro-E payload also contains a co-aligned hard X-ray instrument that is sensitive between 10–600 keV with PIN diode detectors operating in the range 10–60 keV and GSO scintillators operating in the range 30–300 keV. The PIN diodes have an effective area of 160 cm^2, a field-of-view of about 1000 square-arcmin, and a resolving power of about 10, while the GSO has comparable resolving power, an effective area about twice as large, and a field-of-view two orders of magnitude larger.

Additional details and updated information about Astro-E can be found at `http://lheawww.gsfc.nasa.gov/docs/xray/astroe/astroe.html`.

At an energy of 1.5 keV, the *Chandra* microcalorimeter has an effective area of about 400 cm^2, compared to about 160 cm^2 for the XMM gratings and about 100 cm^2 and 50 cm^2 for the "low energy" and "high energy" *Chandra* gratings, respectively, all with comparable resolving power > 100. The microcalorimeter is clearly the spectrometer of choice at higher energies as well, as its resolving power increases linearly with energy (since the energy resolution is approximately constant with energy) and its effective area remains > 100 cm^2 out to almost 10 keV (while the *Chandra* gratings have lower resolving power with increasing energy, and only about 10 cm^2 effective area at the Fe-K lines).

At lower energies, where the resolving power of gratings gets progressively better with increasing wavelength, the effective areas of the gratings actually exceed that of the Astro-E microcalorimeter as the effect of the containing windows of the latter sharply cut off its response. The effective area of the XMM gratings is equal to that of the microcalorimeter at 0.7 keV ($> 100\,\mathrm{cm}^2$), and is still about $50\,\mathrm{cm}^2$ where it cuts off just above 0.3 keV (where the microcalorimeter area is $< 10\,\mathrm{cm}^2$). At still lower energies, the *Chandra* low-energy gratings continue to maintain an effective area $> 10\,\mathrm{cm}^2$ down to 0.1 keV.

4. XMM and High X-ray Throughput

Many of the most fundamental discoveries that have been made in X-ray astronomy have been made through the temporal (rather than the imaging or the spectroscopic) channel of investigation. For example, the determination of the basic nature of the first generation of strong X-ray sources as neutron stars accreting mass from binary companions was the result of the analysis of temporal variability alone. A slightly earlier triumph of temporal variability (but not in X-rays) was the identification of radio pulsars with neutron stars (Gold 1968). Here, there were actually two complementary arguments based upon temporal considerations. First, the high angular velocity of the Crab nebula pulsar (with a period of 33 ms) implied that the surface speed was much too fast to contain stars of more than a neutron-stellar radius. Second, the identification of the secular period increase as arising from the loss in rotational kinetic energy of a neutron star at the Chandrasekhar mass limit matched the required energy source for the Crab nebular luminosity. When early results from *Uhuru* found X-ray pulsars, there were two very troubling aspects to the measurements: first, the periods (of order seconds) seemed much too long to match the luminosities (which were expected to go like the inverse fourth power of the period), and, even more troubling, the putative neutron stars in X-ray sources were speeding up instead of slowing down!

The resolution of this puzzle again came from two complementary temporal measurements on very different timescales: days and seconds (Schreier et al. 1972). The discovery of periodicity in the disappearance of the signal from some X-ray sources on timescales of days suggested to some observers that the signal dropouts might be eclipses in binary systems observed from close to their equatorial planes. This suggestion was clinched when *Uhuru* was able to measure Doppler variations in their second-scale pulse periods which were exactly consistent with the "day-scale eclipse = orbital periods" hypothesis. The total disappearance of the signal was a clear indication that the X-ray source region was much smaller than the ordinary stellar component of the binary system, and the secular speed-up of the pulsations was consistent with the transfer of angular momentum via mass accretion onto the neutron star.

The *Exosat* and RXTE (the *Rossi X-ray Timing Explorer*) spacecraft, in particular, have continued the tradition of providing important temporal (rather than imaging or spectroscopic) X-ray results. Possessing neither true imaging nor competitive spectroscopic capabilities, these two spacecraft provided specific advantages for temporal studies. In the case of the former it was long, continuous observations (as a result of the high elliptical orbit that was designed for lunar

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occultation studies), and in the case of the former it is a very large area that allows for the study of very short timescale effects. The XMM (*X-ray Multi-mirror Mission*) spacecraft has the same two advantages for temporal studies, and contains powerful imaging and spectroscopic tools, as well.

XMM has three X-ray telescopes, each with effective angular resolution of about 20 arc-sec and focal plane CCDs that have effective areas of about 1300 cm^2 at 1.5 keV. As in the case of both *Chandra* and Astro-E, the energy response extends out to about 10 keV. One telescope has only a large-format array of CCDs (referred to as PN) that covers the entire half-degree-diameter field-of-view with a readout format that allows for short-timescale temporal analyses. In contrast, the Astro-E and *Chandra* CCDs have readout modes that generally restrict temporal analyses, and the *Chandra* HRC is considerably less capable (with $< 200\,cm^2$ effective area at 1.5 keV, no energy resolution, a limited X-ray bandpass, and a limited duty-cycle at the Chandra focus). The PN CCDs operate full-time (i.e., during the 80% of each 2-day orbit where it is anticipated that data can be taken), as do the MOS CCDs at the foci of other two X-ray telescopes. Each of these has permanent reflection gratings mounted at the telescope, such that the zero-order transmission (containing about 50% of the incident photons) can be imaged on a CCD array, while the dispersed X-rays can be imaged on another. The net effect is that the effective area for imaging (uncontaminated by dispersed X-rays) at 1.5 keV is about 2500 cm^2, while the effective area at the same energy for the dispersed photons is about 160 cm^2.

The XMM instrument complement also includes a co-aligned 30 cm-diameter optical/UV monitor that is designed to have sensitivity equivalent to a 4-meter ground-based telescope, with a limiting visual magnitude m_V of about 24 in 1000 s.

Additional details and updated information about XMM can be found at `http://astro.estec.esa.nl/XMM/xmm_top.html`.

5. The Near Future

For the past decade, the world community of X- and gamma-ray astronomers has made do with an approximate rate of one new mission launch every two years. These missions have included CGRO (the *Compton Gamma-Ray Observatory*), the Italian-led *BeppoSAX*, and the aforementioned ROSAT, ASCA, and RXTE. The extraordinary conjunction of the launches of *Chandra* and XMM within a period of six months, and the expected relaunch of Astro-E in 4–5 years, is actually augmented by the planned launch of a fourth high-energy mission during this timeframe: a special-purpose small mission to study gamma-ray bursts, HETE (*High Energy Transient Experiment*), for which details can be found at `http://space.mit.edu/HETE/`.

This embarrassment of riches will be followed just a few months later by the launch of yet another observatory, HESSI (*the High Energy Solar Spectroscopic Imager*). Its payload is constructed to perform studies of solar flares with a rotation modulation collimator (for imaging) and detectors that can provide simultaneous coverage over the range 3 keV–20 MeV, with a resolving power of 300 above 1 MeV (where nuclear gamma-ray lines occur and the effective area of the array of gamma-ray detectors is approximately 100 cm^2). The angular resolution of the system is about 2 arc-sec at 40 keV, degrading almost linearly to 36 arc-sec at 20 MeV. In its anticipated three-year lifetime, it is expected to image as many as 1000 flares out to at least 100 keV, and to perform meaningful spectroscopic observations out to 10 MeV on 100 of them.

Additional details and updated information about HESSI can be found at `http://hesperia.gsfc.nasa.gov/hessi/`.

The rate at which new missions will be launched after the year in which four observatory-class missions are launched is still likely to be as high as it was previously. There are several other new missions that are planned for launch at approximately two-year intervals during the next decade.

The first of these is the ESA-led INTEGRAL (the *INTErnational Gamma-Ray Astrophysics Laboratory*), which contains four instruments (one of which is an optical monitor) carried into a highly elliptical 3-day orbit. Like HESSI, the payload is largely devoted to imaging spectroscopy in the range 3 keV–10 MeV, but here the imaging technique is coded masks, and the sources to be studied are celestial rather than solar. The best resolving power is at the higher energies (where the nuclear gamma-ray lines are), but the best spatial resolution is obtained at lower energies. At 10 keV, 100 keV and 1 MeV, the advertised angular resolutions of the masks are 3 arc-min, 12 arc-min, and 2 degrees, respectively, over corresponding fields-of-view of 5 degrees, 9 degrees and 16 degrees. The spectroscopic resolving power at these energies is 7, 14, and 50, with corresponding line sensitivities (in an observation time of 10^6 s) of 2×10^{-5}, 10^{-5}, and 5×10^{-6} photons/(cm^2 s).

Additional information about the INTEGRAL mission can be found at `http://sci.esa.int/integral/`.

As this manuscript is being submitted, NASA has just selected the *Swift* mission for development for a 2003 launch within its Explorer program, to study gamma-ray bursts with considerably better sensitivity than previously possible. Interestingly, *Swift* is not an acronym, but is named for the bird that can quickly change direction in flight. It has three instruments. Its wide field-of-view (2 steradians) burst-detector is 5 times more sensitive than the BATSE instrument on CGRO, and uses a coded mask to determine source locations to arc-minute accuracy, which can be accomplished within seconds for a bright burst. The source position is immediately telemetered to the ground for alerting ground-based observatories, while the spacecraft rapidly turns (like a swift) to train its coaligned X-ray and optical telescopes on the source. The optical telescope is a copy of the XMM optical monitor. The X-ray telescope has an effective area of about 100 cm^2 and is capable of arc-second location within about one minute for the brightest bursts (which are also telemetered immediately). Since NASA hopes to continue the Explorer program at a rate of at least one per year, it is not unreasonable to expect that one or two more high-energy missions will be chosen to be flown within this program before the end of the decade.

Additional details and updated information about *Swift* can be found at `http://swift.gsfc.nasa.gov/`.

NASA has recently issued a call for proposals for GLAST (the *Gamma-ray Large Area Space Telescope*). GLAST concentrates on the very high energy (> 20 MeV) gamma-rays that are beyond the capability of any instrument to be launched since the EGRET *Energetic Gamma-Ray Experiment Telescope* of the

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CGRO. The selected GLAST instrument is expected to have characteristics that allow it to be sensitive to high-energy gamma-rays out to at least 100 GeV with energy resolving power > 10, and with effective area of $> 8000\,\text{cm}^2$ (> 1 GeV) and approximately one-degree single photon location over a field-of-view > 2.5 steradians.

Additional information about the GLAST mission concept can be found at `http://glast.gsfc.nasa.gov/LHEA/`.

Before the end of the decade, it is hoped that the next generation X-ray observatory will be launched. Constellation-X (see White 2000, these Proceedings) will be optimized for spectroscopic investigations, but will naturally have a large increase in aperture to match its spectroscopic capability. The next generation nondispersive imaging spectrometer will have a resolving power in excess of 3000 for Fe-K lines. The better the resolution, the larger the necessary aperture in order to assure that the statistical precision of the data in each energy bin is not larger than the calibration in each resolution element for typical observations. At the fiducial energy of 1.5 keV that was discussed above for the current triad of observatories, Constellation-X is expected to have an effective area in excess of 15,000 cm^2. With this aperture, the angular resolution is not expected to match that of *Chandra*, and is baselined at about 1/4 arc-min. Remembering that X-ray telescopes have grazing-incidence geometries, an aperture this large would require a focal length of order 100 m, if accomplished with a single telescope. The word "constellation" in the name derives from the fact that the baseline design includes multiple launches of extendible telescopes with response out to 10 keV in order to achieve the total aperture, as well as accompanying telescopes that utilize techniques like multi-layers to achieve response out to 50 keV.

Additional information about the Constellation-X triad can be found at `http://constellation.gsfc.nasa.gov/science/staudience.html`.

It is a wonderful time to be interested in studying high-energy plasmas!

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