Edited by Siegfried Röser

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18

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Astronomische Nachrichten /
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Astronomische Nachrichten /
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Suppl. Issue 2: Short Contributions presentetd at the Annual Scientific Meeting of the Astronomische Gesellschaft in Berlin, 2002
ISSN 0004-6337

Astronomische Nachrichten /
Astronomical Notes 324 (2004
Suppl. Issue 3: Short Contributions presentetd at the Annual Scientific Meeting of the Astronomische Gesellschaft in Freiburg, 2003
ISSN 0004-6337

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From Cosmological Structures to the Milky Way

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Germany

Cover
Cluster of Galaxies 1ESO657-55
(VLTUT1 + FORS1)
© European Southern Observatory

Library of Congress Card No.: applied for
British Library Cataloging-in-Publication Data:
A catalogue record for this book is available from the British Library.

Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at http://dnb.ddb.de.

Printing Strauss GmbH, Mörlenbach
Binding Litges & Dopf Buchbinderei GmbH, Heppenheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN-13: 978-3-527-40608-1
ISBN-10: 3-527-40608-5

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Preface

The annual series *Reviews in Modern Astronomy* of the ASTRONOMISCHE GESELLSCHAFT was established in 1988 in order to bring the scientific events of the meetings of the Society to the attention of the worldwide astronomical community. *Reviews in Modern Astronomy* is devoted exclusively to the Karl Schwarzschild Lectures, the Ludwig Biermann Award Lectures, the invited reviews, and to the Highlight Contributions from leading scientists reporting on recent progress and scientific achievements at their respective research institutes.

The Karl Schwarzschild Lectures constitute a special series of invited reviews delivered by outstanding scientists who have been awarded the Karl Schwarzschild Medal of the Astronomische Gesellschaft, whereas excellent young astronomers are honoured by the Ludwig Biermann Prize.

Volume 18 continues the series with twelve invited reviews and Highlight Contributions which were presented during the International Scientific Conference of the Society on “From Cosmological Structures to the Milky Way”, held at Prague, Czech Republic, September 20 to 25, 2004.

The Karl Schwarzschild medal 2004 was awarded to Professor Riccardo Giacconi, Washington, D.C., USA. His lecture with the title “The Dawn of X-Ray Astronomy” opened the meeting.

The talk presented by the Ludwig Biermann Prize winner 2004, Dr Falk Herwig, Los Alamos, USA, dealt with the topic “The Second Stars”.

Other contributions to the meeting published in this volume discuss, among other subjects, X-ray astronomy, cosmology, galaxy evolution, star formation and the Galactic Centre.

The presentation by Alvaro Giménez on the Hot Topic “The Future of ESA’s Space Programme” is not printed in Reviews in Modern Astronomy; the speaker emphasized that the ESA programme is so much in progress at present, that an interested reader will be better informed and continuously updated through ESA’s web-pages.

The editor would like to thank the lecturers for stimulating presentations. Thanks also to the local organizing committee from the Astronomical Institute of the Charles University of Prague, Czech Republic, chaired by Martin Šolc.

Heidelberg, April 2005 *Siegfried Röser*

The ASTRONOMISCHE GESELLSCHAFT awards the **Karl Schwarzschild Medal**. Awarding of the medal is accompanied by the Karl Schwarzschild lecture held at the scientific annual meeting and the publication.

Recipients of the Karl Schwarzschild Medal are

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2004	Riccardo Giacconi: The Dawn of X-Ray Astronomy Reviews in Modern Astronomy 18, 1

The **Ludwig Biermann Award** was established in 1988 by the ASTRONOMISCHE GESELLSCHAFT to be awarded in recognition of an outstanding young astronomer. The award consists of financing a scientific stay at an institution of the recipient's choice. Recipients of the Ludwig Biermann Award are

1989	Dr. Norbert Langer (Göttingen),
1990	Dr. Reinhard W. Hanuschik (Bochum),
1992	Dr. Joachim Puls (München),
1993	Dr. Andreas Burkert (Garching),
1994	Dr. Christoph W. Keller (Tucson, Arizona, USA),
1995	Dr. Karl Mannheim (Göttingen),
1996	Dr. Eva K. Grebel (Würzburg) and Dr. Matthias L. Bartelmann (Garching),
1997	Dr. Ralf Napiwotzki (Bamberg),
1998	Dr. Ralph Neuhäuser (Garching),
1999	Dr. Markus Kissler-Patig (Garching),
2000	Dr. Heino Falcke (Bonn),
2001	Dr. Stefanie Komossa (Garching),
2002	Dr. Ralf S. Klessen (Potsdam),
2003	Dr. Luis R. Bellot Rubio (Freiburg im Breisgau),
2004	Dr. Falk Herwig (Los Alamos, USA).

Karl Schwarzschild Lecture

The Dawn of X-Ray Astronomy[1]

Riccardo Giacconi

Associated Universities, Inc., 1400 16th Street NW, Suite 730,
Washington, DC 20036, USA

1 Introduction

The development of rockets and satellites capable of carrying instruments outside the absorbing layers of the Earth's atmosphere has made possible the observation of celestial objects in the x-ray range of wavelength.

X-rays of energy greater than several hundreds of electron volts can penetrate the interstellar gas over distances comparable to the size of our own galaxy, with greater or lesser absorption depending on the direction of the line of sight. At energies of a few kilovolts, x-rays can penetrate the entire column of galactic gas and in fact can reach us from distances comparable to the radius of the universe.

The possibility of studying celestial objects in x-rays has had a profound significance for all astronomy. Over the x-ray to gamma-ray range of energies, x-rays are, by number of photons, the most abundant flux of radiation that can reveal to us the existence of high energy events in the cosmos. By high energy events I mean events in which the total energy expended is extremely high (supernova explosions, emissions by active galactic nuclei, etc.) or in which the energy acquired per nucleon or the temperature of the matter involved is extremely high (infall onto collapsed objects, high temperature plasmas, interaction of relativistic electrons with magnetic or photon fields).

From its beginning in 1962 until today, the instrumentation for x-ray astronomical observations has improved in sensitivity by more than 9 orders of magnitude, comparable to the entire improvement from the capability of the naked eye to those of the current generation of 8- or 10-meter telescopes. All categories of celestial objects, from planets to normal stars, from ordinary galaxies to quasars, from small groups of galaxies to the furthest known clusters, have been observed. As a result of these studies it has become apparent that high energy phenomena play a fundamental role in the formation and in the chemical and dynamical evolution of structures on all scales. X-ray observations have proved of crucial importance in discovering important aspects of these phenomena. It was from x-ray observations that we obtained the first evidence for gravitational energy release due to infall of matter onto a collapsed object such as a neutron star or black hole. It was the x-ray emission from the high temperature plasmas in clusters of galaxies that revealed this high temperature

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[1] Reprinted with permission of the Nobel Foundation.

component of the Universe, which more than doubled the amount of “visible” matter (baryons) present in clusters.

Table 1: Estimates of fluxes from sources outside the solar system. From Giacconi, Clark and Rossi, 1960.

Source	Maximum Wavelength	Mechanism for emission	Estimated Flux
Sun	< 20 Å	Coronal emission	$\sim 10^6\ cm^{-2}\ s^{-1}$
Sun at 8 light years	< 20 Å	Coronal emission	$2.5 \times 10^{-4}\ cm^{-2}\ s^{-1}$
Sirius if $L_X \sim L_{OPT}$	< 20 Å	? No convective zone	$0.25\ cm^{-2}\ s^{-1}$
Flare stars	< 20 Å	Sunlike flare?	?
Peculiar A stars	< 20 Å	$B \sim 10^4$ gauss Large B Particle acceleration	?
Crab nebula	< 25 Å	Synchrotron. $E_E \geq 10^{13}$ eV in $B = 10^{-4}$ gauss. Lifetimes?	?
Moon	< 23 Å	Fluorescence	$0.4\ cm^{-2}\ s^{-1}$
Moon	~ 20 Å	Impact from solar wind Electrons $\phi_\varepsilon = 0 - 10^{13}\ cm^{-2}\ s^{-1}$	$0 - 1.6 \times 10^3\ cm^{-2}\ s^{-1}$
SCO X-1	2–8 Å	?	$28 \pm 1.2\ cm^{-2}\ s^{-1}$

The prospects for future studies of the universe in x-rays are equally bright. The advent of new and even more powerful experimental techniques, such as non-dispersive high resolution spectroscopy and x-ray telescopes capable of focusing increasingly higher energies over wider fields, ensures a wide opportunity for new astronomical discoveries.

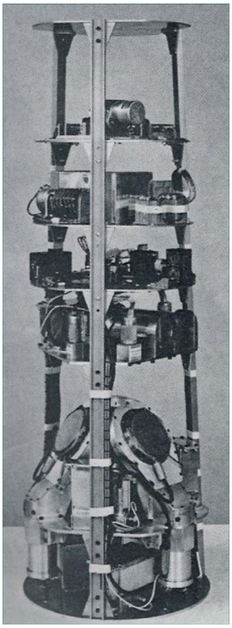

Figure 1: The payload of the June 12, 1962, AS&E rocket. From Giacconi and Gursky, 1974, p.9.

2 The Beginning of X-Ray Astronomy

There had been solar x-ray observations for about 10 years by the Naval Research Laboratory (NRL) group led by Herbert Friedman and several failed attempts to find x-ray emissions from stellar objects (Hirsh 1979) when a group at AS&E (a small private research corporation in Cambridge, Massachusetts) started work in 1959 to investigate the theoretical and experimental possibilities for carrying out x-ray astronomy. Giacconi, Clark, and Rossi (Giacconi et al. 1960) published a document: "A Brief Review of Experimental and Theoretical Progress in X-Ray Astronomy," in which we attempted to estimate expected x-ray fluxes from several celestial sources.

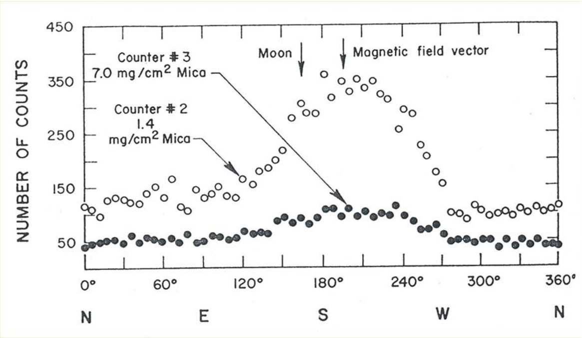

Figure 2: The first observation of Sco X–1 and of the X–ray background in the June, 12, 1962, flight. (From Giacconi, Gursky, Paolini, and Rossi, 1962.

The results are summarized in Table 1. The Sun produced 10^6 x-ray photons cm^{-2}s^{-1} at Earth which could easily be detected with the then-available counters with sensitivities of about 10 - 10^2 photons cm^{-2}s^{-1}. But if all the stars emitted x-rays at the same rate as the Sun, we would expect fluxes at earth as small as 10^{-4} photons cm^{-2}s^{-1}. Other possible sources, such as supernova remnants, flare stars, peculiar A stars, etc., were considered, and great uncertainty had to be assigned to the estimates of their x-ray fluxes. It seemed that the brightest source in the night sky could be the Moon, due to fluorescent emission of lunar material under illumination of solar x-rays.

We designed an experiment capable of detecting 0.1-1 photon/cm^{-2}s^{-1}, 50 to 100 times more sensitive than any flown before. This increase in sensitivity was due to larger area, an anticoincidence shield to reduce particle background, and a wide solid angle to increase the probability of observing a source during the flight. The payload shown in Fig. 1 was successful in detecting the first stellar x-ray source in the flight of June 12, 1962 (Giacconi et al. 1962). An individual source (Sco X-1) dominated the night sky and was detected at 28 ± 1.2 counts cm^{-2}s^{-1}, just below the threshold of previous experiments (Fig. 2). No exceptionally bright or conspicuous visible light or radio object was present at that position (which, however, was very poorly known). An early confirmation of our result came from the rocket flight of April 1963 by the NRL group led by Friedman, which also discovered x–ray emission from the Crab Nebula (Bowyer et al. 1964a).

The truly extraordinary aspect of the discovery was not that an x-ray star had been found but its extraordinary properties. The x-ray radiation intensity from the Sun is only 10^{-6} of its visible light intensity. In Sco X-1, the x-ray luminosity is 10^3 times the visible light intensity and it was later determined that the intrinsic luminosity is 10^3 the entire luminosity of the Sun! This was a truly amazing and new type of celestial object. Furthermore, the physical process by which the x-rays were emitted on Sco X-1 had to be different from any process for x-ray generation we knew in the laboratory since it has not been possible on Earth to generate x-rays with 99.9% efficiency.

Many rocket flights carried out by several groups in the 60's were able to find new stellar sources and the first extragalactical sources. The NRL group and the Lockheed group (led by Phil Fisher) continued to carry out mostly broad surveys, with the notable exception of the Crab occulation experiment by NRL in 1964 (Bowyer et al. 1964b).

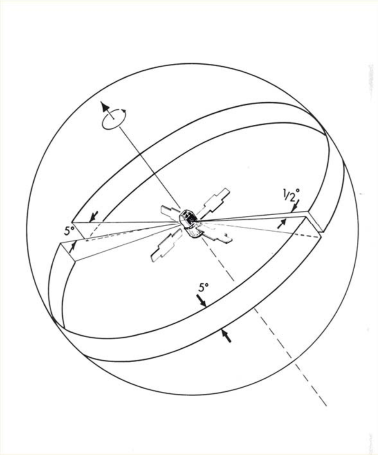

Figure 3: The fields of view of the detectors on the *UHURU* satellite. From Gursky, 1970. Reprinted in Giacconi and Gursky, 1974, p.5.

The AS&E group concentrated on the detailed study of individual x-ray sources. Most significant was the series of rocket flights which culminated in the identification of the optical counterpart of Sco X-1. First the group determined that Sco X-1 could not have the thermal spectrum that would be expected from neutron stars (Giacconi et al. 1965), which implied that an optical counterpart should have magnitude 13. In a first rocket flight to measure the angular size of the source it was found to be less than 7 arc sec (Oda et al. 1965). Thus the source had to be a visible star and not a diffused nebulosity. This led to the sophisticated measurement of the location of Sco X-1 by an AS&E-MIT group led by Herbert Gursky (Gursky et al. 1966), with sufficient precision to enable its identification with a 13th magnitude star (Sandage et al. 1996) which had spectral characteristics similar to an old nova. This renewed interest in a binary star model for Sco X–1 (Burbidge 1967) and Shklovsky proposed a binary containing a neutron star (Shklovsky 1967). However, the absence of x-ray emission from other novas, the lack of indications from either the optical spectra or the x-ray data of a binary system, and the general belief that the supernova explosion required to form the neutron star would disrupt the binary system did not lead to the general acceptance of the idea. The discovery by Hewish of pulsars in 1967 turned the attention of the theorists to pulsar models for the x-ray emitters. But such models also were not quite persuasive given the lack of observed x-ray pulsations. The solution to the riddle of Sco X–1 and similar sources was not achieved until the launch of the *UHURU* satellite, the first of a generation of x-ray observatories.

The proposal to launch a "scanning satellite," which eventually became *UHURU*, was contained in a document written by Herb Gursky and myself and submitted to NASA on September 25, 1963. In this document we described a complete program of x-ray research culminating in the launch of a 1.2 meter diameter x-ray telescope in 1968. This youthful dream was not fully realized until the launch of the *Chandra* X-Ray Observatory in 1999, which, not by chance, had a 1.2 meter diameter mirror. But while the difficult technology development that made x-ray telescopes possible was being carried out, the most fundamental advances in x-ray astronomy were made with relatively crude detectors mounted on orbiting satellites.

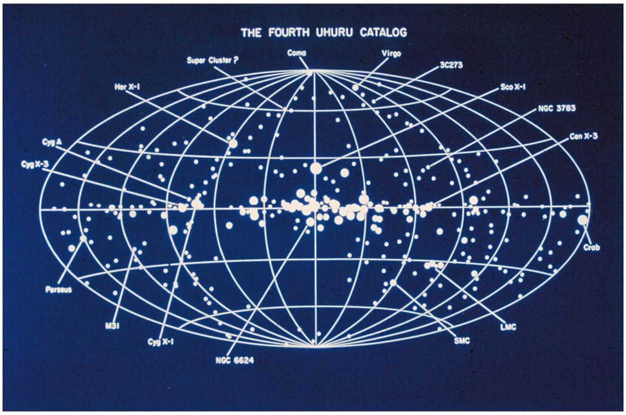

Figure 4: The x–ray sources observed by *UHURU* plotted in galactic coordinates. The size of the dot is proportional to intensity on a logarithmic time scale. From Gursky and Giacconi, 1974, p. 156.

3 Discoveries with *UHURU*

The total amount of time which was available for observation of the x-ray sky during the 60's was about one hour: five minutes above 100 km for each of about a dozen launches. The next step which led us from the phenomenological discoveries to those of great astrophysical relevance occurred on December 12, 1970, when *UHURU*, the first of the Small Astronomy Satellite series, was launched from the Italian S. Marco platform in Kenya. *UHURU* was a small satellite (Fig. 3) which we had labored over at AS&E for seven years between conception, development, testing, and integration.

It was the first observatory entirely dedicated to x-ray astronomy and it extended the time of observation from minutes to years or by 5 orders of magnitude (Giacconi et al. 1971). The field of view of the detector on board the satellite slowly rotated, examining a 5° band of the sky that shifted 1° a day. In three months all the sky could be studied systematically and many new sources could be localized with a precision of about 1 arc minute, often permitting the identification of the x-ray sources with a visual or radio counterpart. This in turn led to an evaluation of the distance, the intrinsic luminosity, and the physical characteristics of the celestial object from which the x-rays originated. Among the 300 new sources which were discovered, we were able to identify binary x-ray sources, supernovas, galaxies, active galaxies, quasars, and clusters of galaxies (Fig. 4). But even more important from a certain point of view was the ability, which was provided by the control system, to slow down the satellite spin and spend a very long time on an individual source to study its temporal variations. It was this special ability which permitted the solution of the fundamental unresolved problem of x-ray astronomy until then, namely, the nature of the energy source capable of producing the large intrinsic luminosity of the stellar x-ray sources.

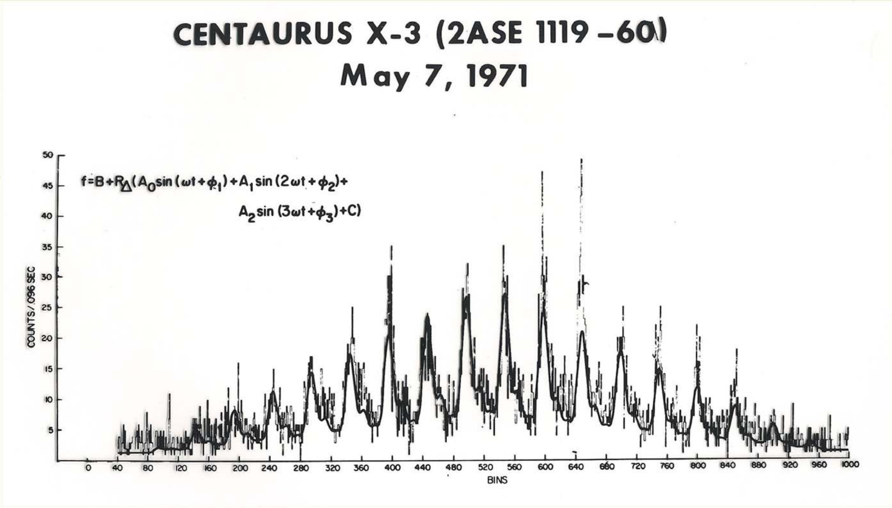

Figure 5: X-ray pulsations of Cen X–3. From Schreier, 1972.

3.1 The Binary X-Ray Sources

In summary, inspection of the data revealed that some x-ray sources (Her X-1 and Cen X-3) (Fig. 5) were regularly pulsating with periods of seconds (Schreier et al. 1972), while others (Cyg X-1) were pulsating with an erratic behavior with characteristic times of less than a tenth of a second as first noted by Minoru Oda, who was a guest at AS&E at the time. Ethan Schreier and I noticed that the average intensity of Cen X-3 was modulated over the span of days and that the period of pulsation itself was changing as a function of the phase of the average intensity, which exhibited occulations (Fig. 6). The explanation for this behavior soon became clear: we were observing a stellar x-ray source orbiting a normal star (Fig. 7). The variation of the pulsation period was then due to the Doppler effect. In 1967 Hewish had discovered pulsars in the radio domain. Was this x-ray source a pulsar in orbit about a normal star? This seemed difficult to accept at the time. A pulsar is a neutron star whose formation is believed to be due to the collapse of a star at the end of its life. The concomitant explosion was believed to disrupt any binary system in which it took place. Joseph Taylor had not yet discovered the binary pulsar.

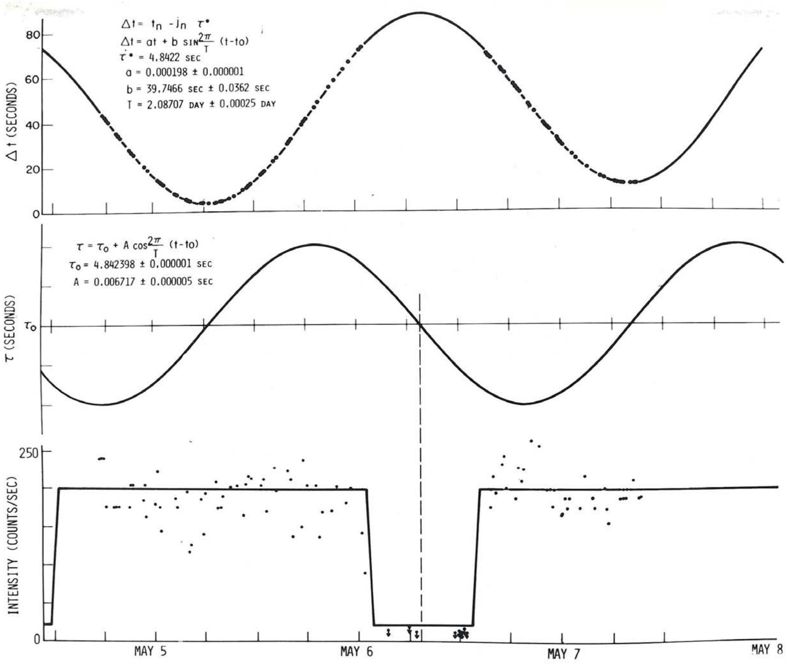

Figure 6: Period variations and occulations of Cen X–3. From Schreier, 1972.

But a new, unexpected, and important finding came to light: the period of pulsation was decreasing rather than increasing with time (Fig. 8). This was true not only in Cen X-3, but also, as Harvey Tananbaum found, the same behavior in Her X-1 (Tananbaum et al. 1972a). Now this was truly embarrassing! In a pulsar the loss of electromagnetic energy occurs at the expense of the kinetic energy of rotation. But in the x-ray sources the neutron star was acquiring rather than losing energy! The explanation was found in the interaction of the gas in the normal star with the collapsed star. Gas from the outer layer of the atmosphere of the normal star can fall into the strong gravitational field of the collapsed star and acquire energies of order of 0.1 mc^2 per nucleon. The accelerated nucleons in turn heat a shock of very high

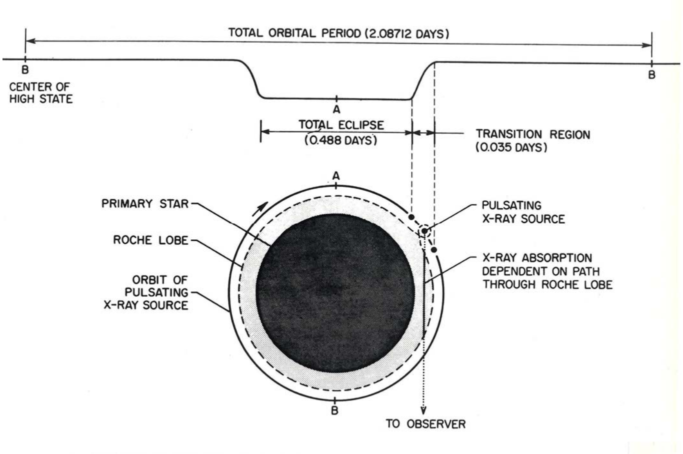

Figure 7: A model of the Cen X–3 binary system. Illustration of R. Giacconi.

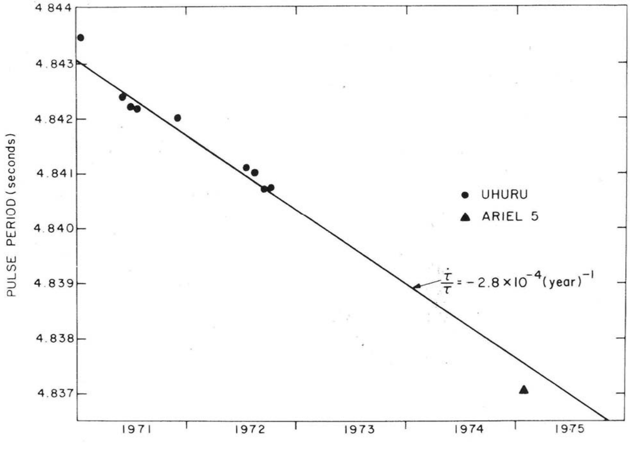

Figure 8: Annual change of Cen X–3 pulsation period. Illustration of R. Giacconi.

temperature above the surface of the neutron star, which emits the observed x-rays (Fig. 9). It is this material infall that gives energy to the collapsed object. This is the model for Sco X–1 and most of the galactic x–ray sources. In the case of a neutron star with a strong magnetic field (10^{12} Gauss), the ionized plasma is confined to the poles of the rotating neutron star, generating the observed periodicities (Fig. 10). For a black hole, there exists no surface with particular structures and therefore the pulsation occurs chaotically (Fig. 11).

The observation by *UHURU* of rapid variability in Cyg X–1 reported by Oda (Oda et al. 1971) was soon followed by the rocket flights of the GSFC and MIT groups. These observations clarified that the observed pulsations were not periodic

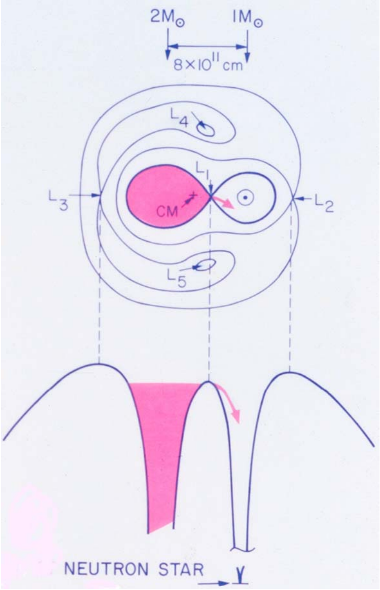

Figure 9: Representation of the equipotentials in the gravitational field of a typical binary x–ray source. Top view and cross section. Illustration of R. Giacconi.

Figure 10: An artist's conception of Her X–1 with accretions occurring at the poles of the magnetic field of the neutron star. Illustration of R. Plourde.

but chaotic (Holt 1971; Rappaport et al. 1971a). By 1974, the GSFC group had achieved a temporal resolution of 1 millisecond and showed large chaotic fluctuations occurring even on this time scale (Rothschild et al. 1974). Such behavior could be expected to occur if the compact object in the binary system (the x-ray source) was a black hole rather than a neutron star. Stimulated by these findings, the search for optical or radio counterparts had become intense in 1971–1972. *UHURU* had obtained a considerably improved position for Cyg X–1 which was made available

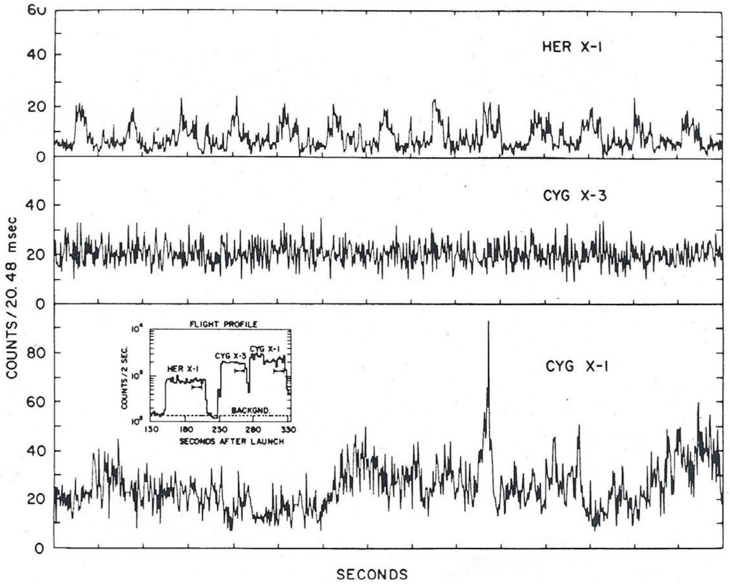

Figure 11: Comparison of the time variability of Her X–1, Cyg X–3, and Cyg X–1. Courtesy of R. Rothschild.

to Hjellming and Wade to aid in the search for a radio counterpart (Tananbaum et al. 1971). More refined positions were obtained by the Japanese group led by Oda (Miyamoto et al. 1971) and by the MIT group (Rappaport et al. 1971b) by use of modulation collimators. Hjellming and Wade (1971) and Braes and Miley (1971) reported the discovery of a radio counterpart. The precise radio location led to the optical identification by Webster and Murdin (Webster and Murdin 1972) and by Bolton (1972) of Cyg X–1 with the 5.6 day binary system HDE 226862. The identification of the radio source with Cyg X–1 was confirmed by the observation of a correlated x-ray radio transition in Cyg X–1 (Tananbaum et al. 1972b). Spectroscopic measurements of the velocity of HDE 226862 also permitted Webster and Murdin to establish that Cyg X–1 was indeed in a binary system. The estimated mass for the compact object was greater than 6 solar masses. Rhoades and Ruffini had shown in 1972 that black holes would have masses greater than 3.4 times the mass of the Sun (Rhoades and Ruffini 1974).

Thus we could reach conclusions regarding Cyg X–1: the Cyg X–1 x–ray emitter is a compact object of less than 30 km radius due to the rapidity of the pulsations and the fact that the pulsations are so large that they must involve the whole object (Giacconi 1974). The object has mass greater than that allowed by our current theories for neutron stars. Therefore the object is the first candidate for a black hole (Fig. 12). Currently there are at least six candidates for galactic x–ray sources containing a black hole (Tanaka 1992).

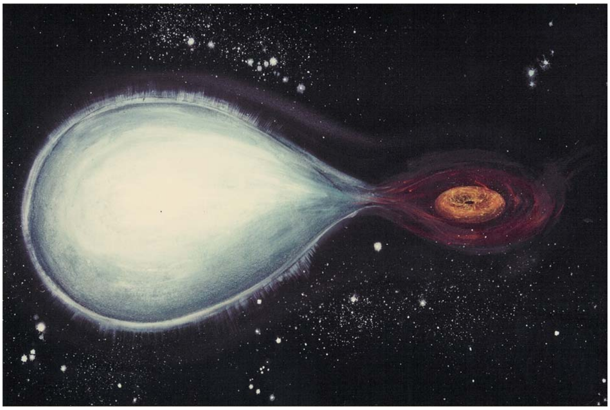

Figure 12: Artist's conception of Cyg X–1. Illustration of L. Cohen.

Table 2: Consequences of the discovery of binary x-ray systems.

- Existence of binary stellar systems containing a neutron star or a black hole
- Existence of black holes of stellar mass
- Measure of the mass, radius, moment of inertia, and equation of state for neutron stars (Density 10^{15} gr/cm^3)
- A new source of energy due to gravitational infall (100 times more efficient per nucleon than fusion)
- A model (generally accepted) for the nucleus of active galaxies and quasars

The consequences of the discovery of binary source x-rays have had far reaching consequences (Table 2). We had proven the existence of binary systems containing a neutron star and of systems containing a black hole. Black holes of solar mass size existed. The binary x-ray sources have become a sort of physical laboratory where we can study the mass, moment of inertia, and equation of state for neutron stars (density 10^{15}gr/cm^3). We had found a new source of energy for celestial objects: the infall of accreting material in a strong gravitation field. For a neutron star the energy liberated per nucleon is of order of 50 times greater than generated in fusion. The above model (of accretion of gas on a collapsed object) has become the standard explanation for the internal engines of quasars and all active nuclei. Recent data seem to confirm the model of accretion on a massive central black hole of $> 10^7$ solar masses as the common denominator among all the active galaxies.

3.2 The Discovery of High-Temperature Intergalactic Gas

The establishment of variability in the x-ray universe, the discovery of the existence of neutron stars and black holes in binary systems, and the discovery of accretion as a dominant energy source were only the first major accomplishments of *UHURU*. Among others was a second very important discovery of *UHURU* and x-ray astronomy, both because of its intrinsic interest and for its consequences in the field of cosmology, the detection of emission from clusters of galaxies. This emission is not simply due to the sum of the emission from individual galaxies, but originates in a thin gas which pervades the space between galaxies. This gas was heated in the past during the gravitational contraction of the cluster to a temperature of millions of degrees and contains as much mass as that in the galaxies themselves (Gursky et al. 1972). In one stroke the mass of baryons contained in the clusters was more than doubled. This first finding with *UHURU*, which could detect only the three richest and closest galaxy clusters and with a poor angular resolution of ½ a degree, were followed and enormously expanded by the introduction of a new and powerful x-ray observatory, *Einstein*, which first utilized a completely new technology in extrasolar x-ray astronomy: grazing incidence telescopes.

4 X–ray Telescopes

Here I must make a short technical diversion to explain the revolution brought about in x-ray astronomy by the telescope technology. When contemplating the estimates made in 1959, I was persuaded that to ultimately succeed in x-ray astronomy, we had to develop new systems quite different from those then in use. Friedman had developed for solar studies a Geiger counter with a thin window which allowed the x-ray to penetrate the interior of the gas volume of the counter. The counter could not decide either the direction of the incoming x-ray or its energy. In order to improve the directional sensitivity, x-ray astronomers used collimators, that is, mechanical baffles which defined a field of view typically of 1°. To improve sensitivity we developed anticoincidence shields against spurious particles and enlarged the area. This is what was done in the discovery rocket of 1962. In 1970 *UHURU* had a very similar detection system. Its improvement in sensitivity was due to the much larger area (800 cm^2 instead of 10) and the much longer time of observation. This led to an increase in sensitivity of about 10^4. It should be noted, however, that in the presence of a background noise, the sensitivity improvement was only proportional to the square root of the area. Thus, further improvement would have required satellites of football-stadium size. Furthermore, all attempts to gain angular resolution by clever systems of baffles (such as the modulation collimators) led to intrinsically insensitive experiments.

The solution which occurred to me as early as 1959 was to use a telescope just as it is done in visible light astronomy (Giacconi and Rossi 1960). This has the great advantage that the flux from a large area of collection is focused onto a small detector, therefore improving both the flux and the signal to noise ratio. In addition, high angular resolution can be obtained within a field which is imaged at once, without scanning or dithering motions, therefore yielding an enormous improvement in exposure time for each source in the field.

The only problem is that an x-ray telescope had to be invented and the technology necessary for its fabrication had to be developed. It ultimately took about

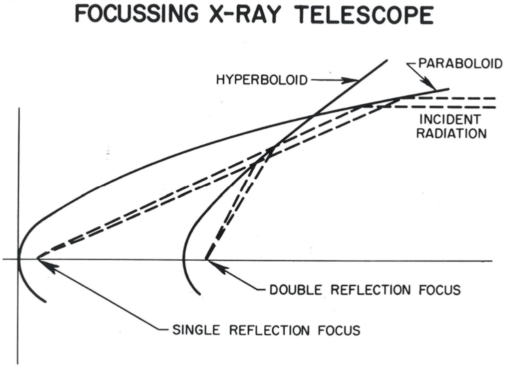

Figure 13: Principle of x–ray grazing incidence telescope. Illustration of R. Giacconi.

20 years between the conception of the x-ray telescope in 1959 and its first use for stellar x-ray astronomy in 1979. An x-ray telescope is quite different from a visible light telescope since the wavelength of x-ray photons is comparable to atomic dimensions. According to Lorentz' dispersion theory, it is clear that the index of refraction of x-rays is less than one, which makes optical systems based on refraction essentially impractical, as was realized by Roentgen himself in his classical experiment of 1895. However, x-rays can be efficiently externally reflected by mirrors, provided only that the reflection takes place at very small angles with respect to the mirror's surface. Hans Wolter had already discussed in the 40's and 50's the possibility of using images formed by reflection for microscopy. He showed that using a double reflection from a system of coaxial mirrors consisting of paraboloid and hyperboloid, one could achieve systems with a reasonably large field (1°) corrected for spherical aberrations and coma. Theoretically, therefore, the system was feasible, although the difficulties of construction given the tiny dimension of the systems for microscopy were impossible to overcome (Fig. 13). I persuaded myself, however, that in the corresponding optical designs to be used for telescopes, which required much larger scales (meters rather than microns), such difficulties would not be severe.

In our 1960 paper we described a system that could achieve sensitivities of 5×10^{-14} erg $cm^{-2}s^{-1}$ and angular resolutions of 2 arc minutes. The improvement in sensitivity was 10^6 - 10^7 times greater than for any detector then current and the improvement in angular resolution about a factor of 10^3. Unfortunately it took a long time to develop this technology (Fig. 14) (Giacconi et al. 1969). The first primitive pictures of the Sun with an x-ray telescope were obtained in 1965. Giuseppe Vaiana took over leadership of our solar physics program in 1967. In 1973 a high resolution x-ray telescope studied the Sun over a period of many months with a field large enough to image the disk and nearby corona and with angular resolution finer than 5 arc seconds (Fig. 15) (Vaiana and Rosner 1978).

It was not until 1979 that a fully instrumented x-ray telescope suitable for the detection and study of the much weaker stellar fluxes could be launched. The new

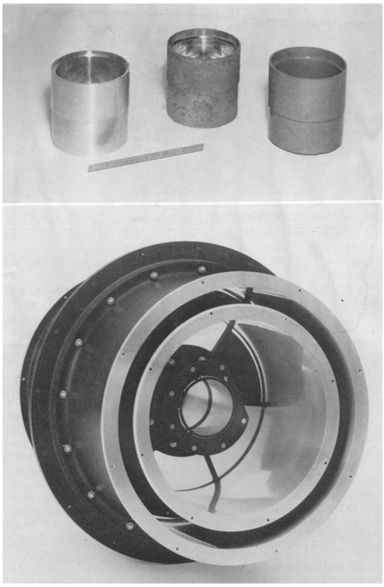

Figure 14: Several early telescope realizations. From Giacconi et al., 1969.

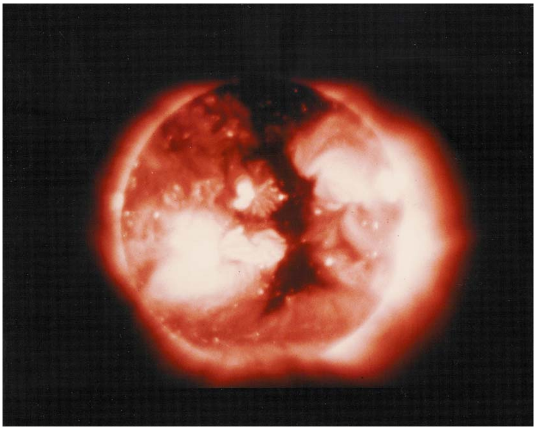

Figure 15: Picture of Sun in x–rays from Skylab. Courtesy of L. Golub, Harvard-Smithsonian Center for Astrophysics.

satellite, which became known as *Einstein,* was a real astronomical observatory (Fig. 16) (Giacconi et al. 1974). In the focal plane of the telescope one could use image detectors with angular resolutions of a few arc seconds, comparable to those used in visible light. The sensitivity with respect to point sources was increased by 10^3 with respect to *UHURU* and 10^6 with respect to Sco X-1. Spectroscopy could be carried out with a spectral resolving power of 500. This substantial technical improvement made possible the detection of all types of astro-

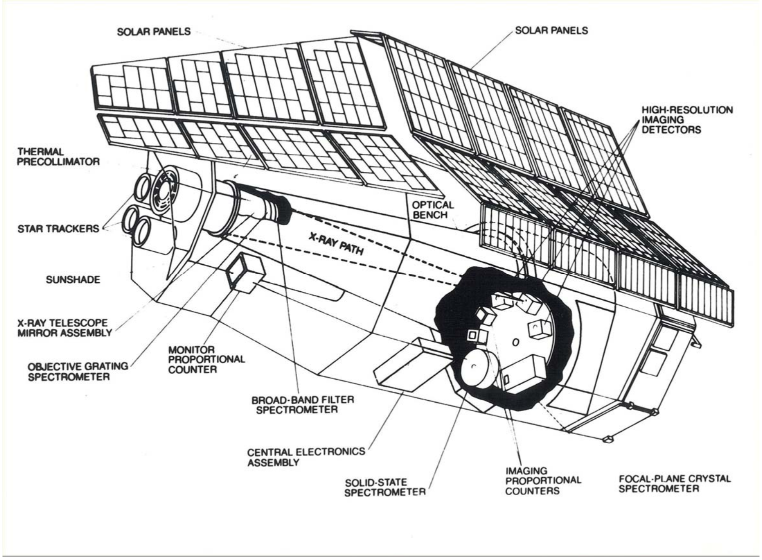

Figure 16: The Observatory *Einstein* schematic representation. From Giacconi et al., 1979.

physical phenomena (Table 3). Auroras due to the Jovian Belts, main sequence stars of all types, novae and supernovae were detected. Binary x-ray sources could be studied anywhere in our own galaxy as well as in external galaxies (Fig. 17). Normal galaxies as well as galaxies with active galactic nuclei, such as Seyferts and B Lac, could be detected at very great distances. The most distant quasars ever detected in visible light or radio could be conveniently studied. The sources of the mysterious, isotropic extragalactic background could begin to be resolved.

Table 3: Classes of celestial objects observed with the *Einstein* Observatory.

- Aurora on Jupiter
- X-ray emission from all types of main-sequence stars
- Novas and supernovas
- Pulsars
- Binary x-ray sources and supernovas in extragalactic sources
- Normal galaxies
- Nuclei of active galaxies
- Quasars
- Groups and clusters of galaxies
- Sources of the extragalactic x-ray background

But to come back to the study of the intergalactic plasma, it is in the study of x-ray emissions from clusters of galaxies that the *Einstein* observations have had some of the most profound impact. The ability to image the hot plasma has given