RICHARD E. GRIFFITHS

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I. Curriculum vitae

General Fields of Research:

Extragalactic optical and X-ray astronomy; galaxy and active galaxy evolution; observational cosmology.
Instrument development for space and ground-based astronomy, especially charge-coupled devices and cameras.

Current primary research interests:

Deep optical and X-ray surveys, star-forming galaxies and galaxy evolution, strong gravitational lensing by galaxy clusters.

Teaching Experience:

Introductory Astronomy, both for scientists and non-scientists. Upper-level astrophysics for astronomy and physics majors. Graduate courses in astrophysics. Average CMU FCE (Faculty Course Evaluation) for all courses = 4.0

Administrative Experience:

Visiting Scientist at NASA HQ, 2008-2013. Program Scientist for the Joint Dark Energy Mission, JDEM; the polarization Explorer GEMS, the ESA Dark Energy Mission Euclid, the Hubble Space Telescope, HST, and the umbrella 'Physics of the Cosmos' Programs. Deputy Program Scientist for the Wide-Field Infrared Space Telescope, (Nancy G. Roman Space Telescope).

Positions Held:

2013-.....	Affiliate Full Professor, University of Hawaii at Hilo
2013-.....	Professor Emeritus, Physics Department, Carnegie Mellon University
2015-2018	Senior Research Scientist, Research Corporation of the University of Hawaii
2008-2013	NASA Visiting Scientist, on leave of absence from Carnegie Mellon University
1996-2013	(Full) Professor, Carnegie Mellon University
1996	Research Professor, Johns Hopkins University
1992-1996	Associate Research Professor, Johns Hopkins University
1983-1992	Associate Astronomer, Space Telescope Science Institute
	Instrument Scientist for the HST Wide Field and Planetary Cameras

1983-1992 Adjunct Associate Professor of Astronomy, Pennsylvania State University

1976-1983 Astrophysicist, Smithsonian Astrophysical Observatory

1975-1976 Research Associate, Leicester University, England

1973-1975 UK Science & Engineering Research Council Post-Doctoral Research Fellow, Leicester University

1971-1973 European Space Agency Post-Doctoral Research Fellow, Saclay, France

Education:

Imperial College, University of London, B.Sc.(Special) in Physics (II(i) Honors), with Ancillary Mathematics, 1968.

University of Leicester, Ph.D., X-ray Astronomy, 1972 (completed 1971)

Membership of National/International Review Panels and Boards (Last 20 Years, excluding NASA HQ roles over the period 2008-2013)

2017 NASA Astrophysics Data Analysis Program Review

2017 NASA Probes Mission Concept Studies Review

2017 NASA Mid-Sized Explorer (MIDEX) Review

2015 NASA Review of the NuSTAR Guest Observing Program for Cycle 2

2016 NASA Astrophysics Data Analysis Program Review

2015 NASA Review of Small Explorer missions in X-ray astronomy

2015 NASA Review of the NuSTAR Guest Observing Program for Cycle 1

2013 NASA Review of Astrophysics Theory Program

2008 NASA Science Review of Small Explorer Missions

2007 NASA Review Panel for *Suzaku* AO-2 observing proposals

2007 NASA Review Panel for RXTE Cycle-11 observing proposals

2003 NASA Review Panel for Technology Readiness and Implementation Plan for Constellation-X

2003 NASA Office of Space Science Review of "Vision Missions" in Astrophysics

2001 - 2008 XMM-Newton Users' Group (Europe + USA)

2000 - 2008 Chair, USA Users' Group for XMM-Newton

1999 - 2008 Astrophysics Working Group for ESA's proposed X-ray Evolving Universe Spectroscopy mission (XEUS)

2001 - 2008 Science Working Group for the Japanese/US X-ray Mission *Suzaku*

1997 - 2012 Board of Directors for the Southern African Large Telescope (SALT)

1998 - 2012 Science Working Team for the Southern African Large Telescope (SALT)

2002 Chair, Review Panel for AGN observations using Chandra X-ray Observatory

1999 NASA and ESA review panels for the investigation of Radiation-Induced Charge Transfer Inefficiency in the Chandra ACIS instrument

1999 NASA-JPL IPAC's Review Panel for the SIRTF First Look Survey

1994, 1999 NASA's Review Panel for SR&T funding of X-ray Instrument Development

1998 NASA's Review Panel for Constellation-X Instrument Development

1995 ESA's Selection Panel for the XMM Science Survey Center

1995 NASA's Review Panel for New Mission Concepts in Space Astrophysics

1990 - 1997 NASA Review Panels for ROSAT and ASCA observations (Chair twice)

1989 ESA's Payload Selection Committee for XMM

1984 - 1986 NASA's Advanced X-ray Astrophysics Facility, AXAF (Chandra X-ray Observatory) Payload Selection and Review Boards

Professional Societies:

Member of the American Astronomical Society

Fellow of the Royal Astronomical Society

Member of the International Astronomical Union

Member of the Society of Photo-Optical Instrumentation Engineers

II. Summary List of P.I. / Co-I. Programs and Research Activities

Ongoing programs have an indefinite completion date ....

2014-2018 P.I. under the NASA Astrophysics Data Analysis Program – Project Title: "X-ray Selected Active Galactic Nuclei at High Redshift: Halo Masses and Sources of the Soft X-ray Background Counts"

2007-2013 Co-I for Chandra X-ray surveys of the COSMOS field

2005 - 2013 Co-I for XMM-Newton Observations of the COSMOS field

2004 Co-I for COSMOS, a 2-sq-degree survey using HST

2000-2007 P.I. for the Commonwealth of Pennsylvania funding of CMU's participation in the Southern African Large Telescope.

1989-2011 Mission Scientist for the European Space Agency's Cornerstone Mission in X-ray astronomy, the Multi-Mirror Mission, XMM-Newton. Guaranteed Time Observations (384 Ks) were made over the period 2000 - 2002.

2001-2007 Member of the Science Working Group for the Japanese/US mission *Suzaku* (formerly Astro-E2). Performance Verification and Guaranteed Time Observations were made over the period 2006-2009.

2003-2004 P.I. for the NASA Small Explorer satellite "Dark Universe Observatory", Phase A study completed 2004.

1985-2004 Co-I. for the Advanced CCD Imaging Spectrometer on the Chandra X-ray Observatory (P.I Garmire at Penn State).

1990-1998 P.I. for the Hubble Space Telescope Medium-Deep Survey (a Key Project for the first 3 years – with about 200 hours per year observing time).

1985-1998 Associate Project Scientist and Co-I. for the Wide Field and Planetary Camera 2 on HST.

1983-1992 Associate Astronomer at the STScI: Instrument Scientist for the HST WF/PC and WFPC2 – research work in this period focussed on instrumentation and the contribution to the x-ray background from AGN and star-forming galaxies.

1990-1995 P.I. for Guest Observer ROSAT observations of quasar survey fields, in ROSAT Cycles 1 - 5.

1993-1997 P.I. for Guest Observer ASCA observations of starburst galaxies, in ASCA Cycles 1 - 5

1988- P.I. for STScI funding of a collaborative effort with KPNO for the development of a Cryogenic Optical Bench and infra-red CCD camera - used from 1992 until 1996 for infrared photometry of Medium-Deep Survey fields. The updated camera (Simultaneous Quad Infrared Imaging Detector - SQIID) is still in active use at NOAO.

1985 P.I. for STScI funding of a ground-based CCD camera, employing a Tektronix CCD. The CCD camera was returned to Steward Observatory in 1989, in exchange for telescope time for spectroscopy of X-ray selected starburst galaxies, a program initiated in 1990.

1983 P.I. for STScI funding of an instrumental upgrade to the University of Hawaii's Image Stabilizing Instrument System (ISIS), a collaboration with Dr. Laird Thomson

1979-1983 (Astrophysicist at the Harvard-Smithsonian Center for Astrophysics, CfA): Coordination of Einstein observatory Medium-Sensitivity Survey (EMSS) and optical identification program, and optical identification of deep-survey X-ray sources, especially in the Pavo field (optical spectroscopy using 4m-class telescopes).

Design, development and operation of a laboratory CCD camera facility for measurement of CCD response to single-photon X-rays in the 0.5 - 8 kev range. This resulted in the first demonstration of the application of CCDs for single-photon X-ray imaging and spectroscopy, and the development of deep-depletion CCDs for X-ray applications. These demonstrations were seminal to the use of CCD cameras on the Chandra and XMM-Newton observatories. This work included supervision and management of engineering and technical support and of software development.

1976-1978 (CfA) Software development and analysis of X-ray data from the High Energy Astronomy Observatory (HEAO-1) Large-Area Sky Survey and Scanning Modulation Collimator experiments (P.I's Gursky and Bradt). Results included the location, optical identification and discovery of the nature of many galactic and extragalactic X-ray sources, including Seyferts, 'narrow-line galaxies' and BL Lac objects.

1972-1976 (Post-Doc. at U.Leicester) Software development and analysis of data from X-ray crystal spectrometer– polarimeter and sky-survey instruments on Ariel V satellite.

P.I. on a star-pointing Skylark rocket experiment in X-ray astronomy, with a paraboloidal mirror and Si (Li) detector, for measurement of interstellar absorption towards the Crab Nebula and measurement of interstellar abundance of Oxygen. Analysis of data from Copernicus satellite; design and development of one- dimensional focusing X-ray mirror and position-sensitive proportional detector.

1971-1972 (ESA Post-Doc. at Saclay) Design and development of solid-state Si(Li) detector systems for X-ray astronomy, including cryogenics and electronics.

1968-1971 (U.Leicester) Ph.D research included design, construction and data analysis from rocket experiments in X-ray astronomy. Measurement of crystal X-ray reflection properties using a double-crystal spectrometer; studies of cosmic-ray background rejection techniques; first cosmic X-ray crystal spectrometer, flown twice on Skylark rockets, once from Woomera, Australia and once from Sardinia (Search for Fe XXV line emission at 6.4 keV in the spectrum of Scorpius X-1). Tutorials and laboratory teaching experience.

1978 - .... P.I. or Co-I on observing runs at ground-based telescopes. These have included the Anglo-Australian Telescope, Kitt Peak National Observatory, Cerro-Tololo Interamerican Observatory, European Southern Observatory, Australia Telescope National Facility, UH-88inch, Steward Observatory, Mt.Stromlo Observatory, Gemini North, Keck Observatory, Subaru Observatory. Most of these observing runs involved the spectroscopy of deep-survey X-ray sources, the spectroscopy of galaxies in the HST Medium Deep Survey, or strong gravitational lenses.

III. Academic and Teaching Activities

A. Advising and Mentoring

(i) Former Doctoral Students with Ph.D. Degree

While a post-doc at Leicester University, I supervised the day-to-day work of several graduate students: Anthony Peacock, Martin Elvis and Mike Watson amongst them - these students were all under the official supervision of Prof. K. A. Pounds. These individuals have all progressed to successful careers and prominent positions in astrophysics - they are still amongst my closest friends and collaborators.

Name (Year of Ph.D. and Institution) Current Position

Adam Knudson (2003 CMU), Industry

Myungshin Im (1995 Johns Hopkins University) see below, under former Postdoctoral Associates

Windsor A. Morgan (1995 Penn State University) Assoc. Professor, Dickinson College

Elizabeth Tolstoy (1996 Space Telescope Science Institute), Postdoctoral Fellow, European Southern Observatory; Professor, University of Groningen, Netherlands

(ii) Former and Current Postdoctoral Associates

Name (Period of Post-Doc. Fellowship) Current Position

Roberto Della Ceca (JHU, 1992-1995) Astronomer, Osservatorio Astronomico di Brera (U Milan)

Stefano Casertano (JHU, 1994-1995) Astronomer, Space Telescope Science Institute

Myungshin Im (JHU, 1996) Astrophysicist, IPAC; Professor and Head of Astrophysics, Seoul National University, Korea

Nathan Roche (JHU, 1995-1996) Research Fellow, Osservatorio Astronomico di Bologna

Kavan Ratnatunga (JHU 1992-1996) , Assoc. Research Professor, CMU 1996 - 2005

Antonella Fruscione (JHU, 1990-1992) Astrophysicist, Harvard-Smithsonian Center for Astrophysics

Lyman Neuschaefer (JHU, 1992-1995) Senior programmer, private industry, Denver, CO

Abraham Naim (JHU, CMU 1995-1997) Senior Analyst, BioInfomatics, Cambridge, UK

Anita K. Romer (CMU, 1997) Lecturer, Sussex University

Andrew Ptak (CMU, 1997-2000) Research Physicist, Johns Hopkins University and NASA Goddard Space Flight Center

Takamitsu Miyaji (CMU, 1999-2003) Research Physicist, CMU 2003 - 2007; Assoc. Prof., Institute of Astronomy, Ensenada, Mexico

Gulab Dewangan (CMU, 2002 - 2005) Research Scientist, IUCAA, Pune, India

Nicholas Schurch (CMU, 2002 - 2005) Research Assistant, Durham University, England

B. Teaching Assignments

(i) Introductory Astronomy, CMU 33-124

Introductory Astronomy was a small class up to and including Spring 1997. In 1998, I expanded the enrolment of this class to a maximum of 140. Observing sessions using 8-inch Meade telescopes have been complemented with the Computational Learning Experiences in Astronomy (CLEA) software.

The FCE numbers below are the Faculty Course Evaluations by the enrolled students, with a maximum rating of 5.

Spring 1997 enrollment 30, FCE 4.0

Spring 1998 enrollment 118, FCE 3.3

Spring 1999 enrollment 98, FCE 3.0

Following my proposal to the Physics faculty, Introductory Astronomy (33-124) further expanded in enrollment from a class of 130 in 1998 and 1999 into two separate classes for the Spring of 2000. One of these classes is for math-proficient students majoring in science and engineering (33-224) and the other is for humanities, business and arts students (33-124). The practical aspects of these classes continue to be taught using small telescopes, and augmented via computerized laboratory exercises and the use of electronic media.

From Spring 2000 - Fall 2003 I taught the Intro. Astro. class (Stars, Galaxies and the Universe 33-224) for scientists and engineers.

Spring 2000 enrollment 40, FCE 3.4

Spring 2001 enrollment 40, FCE 4.15

Spring 2002 enrollment 36, FCE 4.14

Fall 2002 enrollment 30, FCE 4.25

Fall 2003 enrollment 26, FCE 4.0

From Fall 2005, I taught the Intro. Astro. course to humanities students. After reducing the math content in 2006, the FCE improved considerably.

Fall 2005 enrollment 51, FCE 2.5

Fall 2006 enrollment 27, FCE 3.7

Fall 2007 enrollment 28, UCA 3.4 (University Course Assessment)

University of Hawaii at Hilo:

Intro. Astronomy ASTR-110, Spring 2014

(ii) Introduction to Astrophysics, CMU 33-777 (Grad. Course)

'Introduction to Astrophysics' is for first-year grad. students. I initiated this course at CMU in Fall 1997. It is taught as a joint course between CMU and U.Pittsburgh. Enrolment and FCE numbers are for CMU only.

Fall 1997 enrolment 4, FCE 4.7

Fall 1998 enrolment 6, FCE 4.3

Fall 1999 enrolment 3, FCE 4.5

Fall 2000 enrolment 6, FCE 4.75

Fall 2001 enrolment 8, FCE 4.00

Spring 2004 enrolment 5, FCE 4.75

Spring 2005 enrolment 8, FCE 4.50

Spring 2006 enrolment 6, FCE 4.50

(iii) Astrophysics of Stars and the Galaxy CMU-467

Upper level astrophysics track courses were initiated in 2003, reflecting the general interest of physics majors in astrophysics.

Fall 2004, enrolment 4, FCE 4.0

(iv) UHH Gravitation & Cosmology ASTR-460

Observational Cosmology ASTR-499 Fall 2014

Gravitation & Cosmology. ASTR-460, Spring 2016, Fall 2018

C. Carnegie Mellon University Committees (until leave of absence in 2008)

(i) CMU Physics Department

2007 - 2008 Advisor to the McWilliams Cosmology Center Committee

2005 - 2008 Graduate Qualification Exam Committee

2000 - 2005 Physics Department Planning Committee

2000, 2003 Astrophysics Theory Search Committee

2001 Postgraduate Curriculum Task Force

1999 Committee to Search for a new Head of Department

1998 Undergraduate Credits Task Force (Chair)

1998 Graduate Student Special Oral Exam Committee

(ii) Mellon College of Science

1997 - 1999 Tenure Review Committee

IV. OUTREACH ACTIVITIES (last ten years)

2013 "Large Telescopes in Space", May 2013

2013 Public Lecture on "Science with the Hubble Space Telescope", U. Hawaii at Hilo, Nov. 2013

2015 Public Lecture on "25 Years of Science with Hubble", Imiloa Astronomy Center, Mar. 2015

2015 Founding of the Astronomy Club at Polestar Gardens, Pahoa - monthly activities

2019 "Thirty Years of Science with the Hubble Space Telescope" UHH Outreach Program

2019 Participation in 'Journey through the Universe', local K-12 schools

V. Past and Current Research Interests

A. The Evolution of Extragalactic X-ray Sources

Over the past nearly four decades, a major focus of my research work has been on the optical identification and interpretation of the faint X-ray sources detected in the Deep Surveys with X-ray telescopes (NASA's Einstein Observatory, the German/US/UK mission ROSAT, the Japanese - US mission ASCA, the Chandra X-ray Observatory and the ESA mission XMM-Newton). The purpose of this research was initially to identify the types of object which contribute to the extragalactic X-ray flux, and to estimate their total contributions by measuring their luminosity functions and the rate at which these functions evolve with cosmological epoch. In recent years the emphasis of this work has shifted to the understanding of black hole growth and evolution, the relationship with the host galaxy, and the evolution of normal galaxies in X-rays.

This work thus entered a new phase with the Deep Surveys performed with the CXO and XMM, both of which have extended the energy range of large orbiting X-ray telescopes up to 10 keV. The origin of the X-ray background was largely solved using ROSAT at soft X-ray energies (it comprises various classes of Active Galactic Nuclei (AGN) and starburst galaxies), but most of the energy in the X-ray background lies outside the range of the earlier X-ray telescopes. By pushing the upper energy limit to 10 keV, the CXO and XMM observatories have finally solved this problem to a large degree. The most consistent current hypothesis is that the X-ray emission comes from the AGN that are present in the nuclei of all giant galaxies, but most of this energy is absorbed so as to be undetected in soft X-rays (following Setti and Woltjer 1979). A considerable fraction of the total accretion energy output of the universe is originally in the form of X-rays which are absorbed - the energy is reradiated in the infrared.

For the earlier ROSAT and ASCA observing programs, I was P.I. on the U.S. side of a collaboration with Boyle, Shanks and Stewart in the U.K. (see the series of papers entitled "A ROSAT Deep Survey..." listed in the Bibliography). Rapid progress in the understanding of the soft X-ray background was made using these deep surveys. We measured the x-ray emission of AGN and the other sources in fields previously surveyed for UV-excess objects. Optical follow-up at the Anglo-Australian Telescope led to the identification and redshifts of large numbers of AGN (well over 100) in these fields. Results indicated that AGN at redshifts of about one (Einstein) and 1.5 (ROSAT) dominated the brightest discrete sources (fluxes just above 10^{-14} ergs cm^{-2} s$-$1, 0.5 - 2 keV) detected individually above the unresolved residual background. This enabled us to measure the evolution of the X-ray luminosity function of AGN, with the conclusion that the evolution is almost as rapid as it is for opticaly selected quasars, with a cut-off in the evolution beyond a redshift of about 2. About 60–70% of the X-ray background as observed by ROSAT was accounted for by AGN. This work was extended to higher energies (about 8 keV) using the Japanese satellite ASCA - I was P.I. on the ASCA deep surveys performed in 1997 on regions which we had previously studied with ROSAT. More recent work with XMM-Newton and Chandra has indicated that the lower-luminosity Seyferts reach a peak in their cosmic evolution at later times than the higher luminosity objects: this is sometimes referred to as cosmic-downsizing.

A minority of the sources in the ROSAT deep surveys appeared to be star-forming galaxies with narrow optical emission lines, and early-type galaxies. Several examples of these galaxies were originally found at the level of the Einstein Medium-Sensitivity Survey, by performing spectroscopy of: (i) galaxy candidates from the Extended MSS, and (ii) candidates resulting from a correlation between the Infrared Astronomy Satellite (IRAS) and Einstein Observatory databases. This latter work was done in collaboration with Fruscione, using guaranteed time at Steward Observatory obtained in exchange for the development of a CCD camera (Fruscione and Griffiths, 1991). It has been demonstrated that infrared imaging is also a useful discriminant in establishing the nature of these starburst galaxies.

I was P.I. for observations of individual starburst galaxies using the Japanese - US X-ray astronomy satellite ASCA (Advanced Satellite for Cosmology and Astrophysics), in collaboration with Heckman and others, with the goal of establishing whether these galaxies contain a component of hard X-ray emission from X-ray binaries as well as soft X-ray emission from supernova remnants. Analysis of these data indicated the presence of both a soft thermal component at a temperature of about 1 keV (outflowing hot wind), and a harder component which may arise in the combined emission from X-ray binaries.

Observations using the Advanced CCD Imaging Spectrometer on the Chandra X-ray Observatory

My development work on charge-coupled devices for X-ray imaging and spectroscopy during the period 1978-1983 established the unique applicability of these devices for X-ray astronomy and led to my involvement with the CCD camera on the Chandra X-ray Observatory. CCD's have since become the detectors for the primary instruments on all major X-ray astronomy missions.

I was co-Investigator for the Advanced CCD Imaging Spectrometer (ACIS) on Chandra from 1985 to 2004 (the P.I. is Gordon Garmire at Penn State Univ.). This instrument has allowed us to pursue the nature of the faintest X-ray sources accessible to Chandra, sources two orders of magnitude fainter than the Einstein Observatory deep survey limit, and nearly an order of magnitude fainter than the ROSAT limit. The CXO deep survey of the Hubble Deep Field has been used to investigate the optical identifications of these sources. The changing constitution of the X-ray number counts has thus been established, i.e. with normal galaxies dominating the number counts at fluxes below about 10^{-16} ergs cm^{-2} s-1 (0.5 – 2 keV), with AGN (and clusters) dominating at higher fluxes. After removal of the individual AGN from the deep survey images, fluctuations in the remaining X-ray counts have shown that the number-flux relationship continues to rise at low fluxes, and this can only be due to normal galaxies. The 'stacking' method has been used to show that the normal galaxy populations are responsible for the high numbers of X-ray sources two orders of magnitude fainter than the detection limit for discrete sources. I have used the combined datasets from the HST and Chandra to show the relative importance of the different morphological galaxy types in terms of their evolution in X-rays. This work currently continues on the Chandra deep survey fields.

In order to probe further the X-ray emission from individual starbursts and AGN, I have investigated the X-ray emission from M82 as part of the ACIS team observations. A ULX is responsible for a large fraction of the hard X-ray emission from M82, which also has a hard extended thermal component which is overpressurised relative to its surroundings.

Involvement with ESA's X-ray Multi-Mirror Mission, XMM-Newton

In 1989, following an open proposal and NASA science peer review, I was appointed as Mission Scientist for ESA's "High Throughput Spectroscopy Mission" in X-ray astronomy, the X-ray Multi-Mirror Mission, XMM. I was thereby a member of the Science Working Team (equivalent to that of Interdisciplinary Scientist on a major NASA mission). There are a total of five Mission Scientists, two of whom are funded by NASA for participation in XMM (present funding is at the level of about $160K per year). I was a member of the Payload Selection Committee in 1988, and was later active in ESA reviews of the scientific instruments and the data operations center, and in the selection of the Science Survey Center. In addition, I represented the other Mission Scientists in my role as a member of the Science Calibration Team. The Mission carries large-area X-ray mirrors, with two primary instruments, the European (X-ray) Photon Imaging CCD Camera (EPIC) and a Reflection Grating Spectrometer (RGS), both instruments using CCDs as the detectors. The observatory also has a piggy-back Optical Monitor, which is a separate optical telescope.

My funded appointment as Mission Scientist was extended through 2008, with funding declining in the latter years, but compensated with successful General Observer programs.

My research programs with XMM-Newton complemented those with the CXO: viz. deep surveys (of the HDF, the Groth-Westphal field and the COSMOS field), together with detailed spectroscopy of nearby Seyfert galaxies (e.g. NGC 4151 and MCG-5-23-16).

More recent work included the analysis of XMM-Newton and *Suzaku* data on the X-ray spectra of Active Galactic Nuclei, especially the region of iron-line emission and absorption around 6.4 keV. These studies have centered on the possible variability of the red wing of the iron line, implying changes to the innermost part of the accretion disk where the line is broadened by the effects of general relativity.

Research work using XMM-Newton and *Suzaku* has also included studies of the spectra and variability of the ultraluminous X-ray sources in nearby galaxies, with the goal of trying to establish the nature of these sources and the mass of the black holes which power them.

B) Evolution in Galaxy Morphology: the HST Medium Deep Survey 1992-1998 and HST COSMOS 2003-2012

The HST Medium Deep Survey (MDS) was a Key Project which used the Wide Field Camera in Parallel mode, i.e. the camera was used to make images of randomly positioned fields while other HST instruments were used on the primary targets of observation. This has been the largest General Observer program undertaken with HST (about 300-400 hours of observing time per year during the period 1992 - 1997) and the only one of a serendipitous nature. Originally approved for the first three years of the HST observing program, the survey was successful in competing for observing time and funding each year. The HST Cycle 6 time allocation committee commented that *"The MDS is one of HST's success stories. It has been an extremely productive program, done to very high standards, addressing many important issues. The team has done a remarkable job in meeting their ambitious goals. An extremely valuable database will accrue to the community, and excellent science will be done along the way."*

The Project was led and organized in such a way as to maximize the productivity and visibility: the resulting publications and the success in attracting funding are testament to this. There were several factors which contributed to this success:

(a) the overriding philosophy was to keep the project as simple as possible for HST operations, to use parallel WFPC2 data at every opportunity (some approved parallel programs failed to receive any data for several years and then received only limited datasets); (b) the project was led from my research group at Johns Hopkins University, in close proximity to the HST operations personnel at the STScI; (c) the project was tightly coordinated amongst the Co-I groups, with "working groups" set up for individual science tasks. All personnel were kept in close communication with the project via e-mail and frequent telephone conferences; (d) the management and coordination of the project were key factors in the continued funding, and these factors were assessed annually by a review panel of scientists and managers at the STScI.

The Survey data provided a unique and homogeneous database optimized to address a wide range of astronomical problems, both Galactic and extragalactic. Intimate knowledge of the Wide Field Camera's charge-coupled devices and their calibration problems (gained during my position as Instrument Scientist at STScI 1983-1992) was used to extract information on the faintest objects which HST can detect. The parallel MDS fields typically contained several hundred galaxies per field and the MDS was a statistical survey of the stars and galaxies in these fields. Exposures ranged from one orbit to about ten or twenty orbits in the most favorable cases, and broad-band filters were used to gain as much sensitivity as possible.

The focus of the CMU group was on the statistical properties of the complete galaxy catalog. These studies included the broad morphological properties of faint galaxies, their merging statistics, and studies of gravitational lensing.

We made available from the MDS a catalog of 150,000 galaxies at the web-site http://astro.phys.cmu.edu/mds; the complete publication list is at http://astro.phys.cmu.edu/mds/mds_publ.html. As well as using the data from the MDS proper, we applied the MDS pipeline processing to other fields such as the Hubble Deep Field (HDF), the Groth-Westphal strip and the Canada-France Redshift Survey fields, where redshift measurements were more plentiful than for the MDS fields (Im et al 1999).

The main results from the MDS were as follows:

(i) Although perhaps the most oft-cited papers from the MDS are those describing the number counts and evolution of galaxies after rough morphological classification (Glazebrook et al. 1995, 1998 and Driver et al. 1995), these papers were based on eyeball morphology, confirmed by an automated analysis which used parameters of compactness and asymmetry (Abraham et al. 1996). Using these methods, morphologies were studied with a precision adequate for classification on the normal Hubble scheme to a limiting magnitude of about $I_{814} \sim 22.0$ mag for most MDS fields. These results established that irregular and peculiar galaxies are responsible for the long-standing problem of the excess in faint blue galaxy counts.

(ii) Basic galaxy information (e.g. scale lengths) was determined to considerably fainter limits, at least $I_{814} \sim 24$ - 25 mag. in the deeper of the MDS fields (Casertano et al. 1995, Roche et al. 1996, 1997, 1998). The automated measurement of galaxy sizes thus led to results on the evolution of size with redshift. The key result, that galaxies were much smaller at high redshift, was initially established from aberrated WF/PC data (Casertano et al. 1995) but was later confirmed and modelled using parallel data from WFPC2 (Roche et al.). Sizes, magnitudes, colors and crude classifications were based on two-dimensional model fitting to undeconvolved images (Ratnatunga et al. 1994). Automated parameterization of the residual galaxy images, following subtraction of the best-fitting disk or $r^{1/4}$ profile, was performed using Kohonen's self-organizing maps (Naim et al. 1997). Such a scheme becomes necessary at redshifts exceeding unity because galaxies at high redshift no longer fit the simple Hubble classification scheme. Using samples for which spectroscopic data or reliable photometric redshifts were available, the Kohonen SOM analysis showed a trend towards increasing degrees of clumpiness and isophotal central displacement towards higher redshift, especially in the HDF data. These trends have since been confirmed in the HST UDF data.

(iii) The surface brightness evolution of E/S0 galaxies accounted for their Luminosity Evolution (described by the Pure Luminosity Evolution model, PLE), viz. about 1 mag. between redshifts of 0.2 and 0.9. As a harbinger of future work, we found evidence for weak gravitational shear in the vicinity of E/S0 field galaxies in the MDS (Griffiths et al. 1996), and have used this effect to constrain their masses and the cut-off radii of their dark matter halos. This work was statistical in nature, with a sample of elliptical galaxies selected morphologically at I = 22, while fainter exponential (disk dominated) galaxies in their vicinity were assumed to be at higher redshift. The position angles of the major axes of the background disk galaxies were tilted on average by about 1^o as a result of weak lensing by the gravitational field of the foreground ellipticals. A better understanding of the distribution of dark matter around elliptical galaxies awaits the repeat of this kind of study, using galaxies at measured redshifts. On the assumption that the average redshift of the foreground ellipticals was about 0.6 (based on sizes, magnitudes and colors), and that the average background galaxies were at z = 1, then the average mass was found to be $10^{12} M_{\odot}$ and the dark matter truncation radius was found to be a bout 50 half-light radii.

(iv) E/S0s should have appeared in the MDS data with $I < 22.5$ at $z \sim 3$, but they did not. The deeper archival fields and HDF data later confirmed this finding. If the density Φ^* for E/S0s falls beyond $z > 1.5$, then what were the precursor objects? i.e. in what form were the objects which became the E/S0s ? After subtraction of the best-fitting $r^{1/4}$ model images of HDF objects, the residuals show disky components and often multiple nuclei.

(v) We found an intrinsic brightening of ~ 1 mag. for Sabc galaxies between $z = 0.2$ and $z = 0.9$ (Roche et al. 1998). The PLE prediction was less than this, but the size-and-evolution model (SLE) of Roche et al. gave good agreement. In this latter SLE model, both L^* and the half-light radius r_{hl} evolved. The SLE model included a radial dependency of star formation history, whereby the light output for galaxies at high z was dominated by the inner regions, whereas at $z < 1.5$ the light output was dominated by slowly evolving regions far from the nucleus where evolution of the star formation rate was less rapid.

(vi) As found by Glazebrook et al. and Driver et al., the MDS data were well fitted by a model in which the irregular galaxy population was dominated by a steep, dwarf-dominated LF, (as originally found by Marzke et al. 1994). Their colors are those of Sd galaxies, and the evolution in surface brightness was found to be about 1.4 mags. between $z = 0.2$ and $z = 0.9$. The data were well modelled by a SFR similar to that of late-type spirals, but including large short-term variations. The net result was approximated by two LF populations: (i) a steadily evolving SFR peaked at $z \sim 1$, and (ii) a bluer, episodic starburst component. There was no evidence for size evolution in these populations.

(vii) The peculiars (characterized by large asymmetry and substructure, with frequent evidence for nucleation and features such as streamers, trails or loops), have undergone an evolution in brightness similar to that of spiral galaxies. The peculiars seemed to be dominated by Blue Nucleated Galaxies (BNG's), i.e. galaxies with merger-induced central starburst regions, and may be a stage in the evolution of giant galaxies. Mergers of Sabc disk-plus-bulge galaxies may plausibly result in the blue nucleated galaxies. The overall evolution may then be from Sabc galaxies to peculiar BNGs to S0s, in order of merging

(viii) The MDS team found evidence for weak cosmic shear caused by the large-scale distribution of dark matter. The signal was present in the data at the level of about $\sim 2.5\%$.

When originally presented, this was the first indication of a detection of cosmic shear from large-scale structure.

The results of the HST MDS have generally been superseded in later years by results from the Hubble Deep Fields, the GOODS and GEMS surveys, and the 2-square degree COSMOS survey. All of the basic findings of the MDS have been vindicated in these later surveys. I am a co-I on the COSMOS survey, which we have followed up with X-ray surveys using XMM-Newton and the CXO.

C Recent Research Interests, post 2000-

In 2003-4 I was PI for the NASA Small Explorer satellite mission "Dark Universe Observatory", which was an X-ray telescope proposal based on the German ABRIXAS mission (1999, failed in orbit). Out of 35 proposals, DUO was one of five selected for a Phase-A study which was completed in 2004 but was not continued by NASA because of budget problems. The DUO mission was re-proposed by MPE in Germany as the eROSITA experiment, launched on a Russian satellite mission in July 2019. One of the main goals of this kind of X-ray Survey experiment is to measure the X-ray emission of at least 10,000 clusters of galaxies in order to measure the number counts of clusters as a function of redshift, and the fluctuations in these numbers with redshift. X-ray luminosity is an indicator of the mass of a cluster, and the measurements can be used to measure the equation of state parameter for dark energy.

One of the main sources of systematic error in the use of X-ray clusters of galaxies for cosmology is the fraction of the X-ray emission which arises from AGN, and the evolution of this fraction with redshift. At a redshift of about one, AGN were much more active than they are in the local universe and the combined X-ray emission from these AGN within a cluster may be a significant fraction of the total emission from that cluster (certainly more than 10%). Furthermore, the presence of X-ray emission from the AGN changes the relationship between mass and X-ray luminosity for the clusters. This relationship is therefore expected to be a function of redshift, and it is vitally important to quantify this. AGN have clearly had a major influence on nearby massive clusters: jets and outflows emanating from them have created 'bubbles' which effectively stop the 'cooling flows' and raise the entropy floor.

Using the combined datasets from the CXO, XMM-Newton and the HST on the COSMOS and other fields, I have been measuring the AGN content of clusters of galaxies as a function of redshift by performing optical spectroscopy of the AGN candidates (using Keck DEIMOS). The results of this work (in collaboration with G.Hasinger at IfA) were used as input to my NASA-funded (Astrophysics Data Analysis Program) project to study the X-ray halo occupation distribution (HOD) of AGN.

VI. Project Support (NASA, unless otherwise stated)

Note All NASA research funding was terminated in 2008 on taking up a NASA HQ appointment, and no funding applications could be submitted until 2014

P.I. under the Astrophysics Data Analysis Program – Project Title: "X-ray Selected Active Galactic Nuclei at High Redshift: Halo Masses and Fluctuations in X-ray Background Counts"

2015-2018 : $953K total

Member of the Science Working Group for Suzaku

2005 - 2008 : $160,000.

P.I. for the "Dark Universe Observatory"

2003-2004: $450,000 for the Phase A study, completed in June 2004. DUO was a collaboration with science teams at MPE, Germany and GSFC. Ball Aerospace was the industrial contractor and was not selected for further study.

P.I. for CMU participation in SALT, funded by the Commonwealth of Pennsylvania

2000 - 2008 : $250,000 per year for the past five years and expected to continue at that rate for at least the next three years.

Mission Scientist for the European Space Agency's XMM-Newton: 1989 - 2008:

(1 of 2 Mission Scientists in the USA)

Annual funding ramped up from $94K in 1992 to $169K in 2002 and continued at that level until 2005, then lowered to a travel budget and partial summer salary support only.

P.I. or Co-I on XMM-Newton General Observer programs:

2002-2003: Observations of NGC 4151 - $9,000

2003-2006; Observations of the COSMOS HST field - $28,000, shared with T.Miyaji.

2006-2007 (P.I.): Observations of NGC7582: A Seyfert 2 analogy of Narrow-Line Seyfert I's - $46K

2007-2008 (P.I.) : Observations of Ultraluminous X-ray source Holmberg IX X-2 - $55K

Co-I. for the Advanced CCD Imaging Spectrometer (ACIS) on the Chandra X-ray Observatory (CXO):

1996 - 2004: Co-I award from Penn State University. Funding through launch (1999) plus 5 years

Annual funding ramped up from $70K in 1998 to $110K per year from 2000 through 2002, with phasing out of this funding by Sept. 2004.

Co-I on the HST General Observer program COSMOS - P.I. is Scoville at CalTech

2003-2007: $94,000

P.I. for the Medium Deep Survey (Key Project) on the Hubble Space Telescope : 1991 - 1998, with ten Co-Investigators

Cycle 1, 1991 - 1992: $523,000

Cycle 2, 1992 - 1993: $825,000

Cycle 3, 1993 - 1994: $675,000

Cycle 4, 1994 - 1995: $625,000

Cycle 5, 1995 - 1996: $300,000

Cycle 6, 1996 - 1997: $220,000

Co-I. (and Associate Project Scientist) 1992 - 1998 for the Hubble Space Telescope Wide-Field and Planetary Camera II, with Trauger et al. :

This Co-I position was funded at approx. $140K per year from 1992 through 1998

P.I. for analysis of Archival HST data on the Hubble Deep Field, with Ratnatunga, Ostrander:

1996 - 1997: $53,000

Co-I. for analysis of Archival HST data on Clusters of Galaxies (with Ratnatunga, Naim) :

1996 - 1998: $80,000

Co-I. for analysis of Archival Parallel WFPC2 HST data (with Ratnatunga as P.I.) :

1998 - 1999: $80,000

Co-I. for analysis of Archival Parallel ACS HST data (with Ratnatunga as P.I.) :

2002 - 2003: $80,000

Co-I. for analysis of Deep Survey data from the Chandra X-ray Observatory, CXO, with Boyle, Shanks, Stewart, Georgantopoulos

Program: "CXO Deep Survey of the Herschel Deep Field"

Cycle 1, 2000 - 2001: $30,000

Co-Investigator for analysis of Emission-Line Galaxy Survey data from the Chandra X-ray Observatory, CXO with Boyle, Shanks, Stewart, Georgantopoulos

Program: "Near-Infrared Emission Line Galaxies"

Cycle 1, 2000 - 2001: $30,000

Principal Investigator for analysis of Deep Survey data from the Roentgen Satellite, ROSAT (German/US/UK) : 1990 - 1995, with Boyle, Shanks, Stewart, Georgantopoulos

Program: "X-ray Properties of Optically-selected QSO's "

Funded at approx. $20K per year from 1990 through 1994, Cycles 1 through 4 inclusive.

Principal Investigator for analysis of data from the Advanced Satellite for Cosmology and Astrophysics, ASCA (Japan/US), with Della Ceca, Heckman:

1993 - 1998 “Starbursts and Winds in Dwarf Galaxies”
Funded at approx. $40K per year from 1994 through 1998, Cycles 1 through 5 inclusive.

Principal Investigator for an Astrophysics Data Program Award 1991 - 1992
“Starburst Galaxies and the X-ray Background” 8.1.91 to 7.31.92 $28,000.

RICHARD E. GRIFFITHS : BIBLIOGRAPHY

I. PAPERS IN REFERRED JOURNALS

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ApJL : Astrophysical Journal Letters

ApJS : Astrophysical Journal Supplement

AJ : Astronomical Journal

MNRAS : Monthly Notices of the Royal Astronomical Society

PASJ : Publications of the Astronomical Society of Japan

SPIE : Proc. Society of Photo-Optical Instrumentation Engineers

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