Schlußbericht

Zum Vorhaben FKZ 50 OR 9908 0

"Metagalaktische Röntgenhintergrund"

1 Aufgabenstellung und Voraussetzungen

1.1 Aufgabenstellung

Das Vorhaben "Metagalaktische Röntgenhintergrundstrahlung – Aktive Galaxien im frühen Universum" hatte, anknüpfend an das Projekt "Die Leuchtkraftfunktion der Seyfert-Galaxien" (1997-1999) zum Ziel, die durch die tiefen Himmelsdurchmusterungen mit dem ROSAT-Satelliten gewonnenen Erkenntnisse auf eine gesicherte physikalische Basis zu stellen und damit verbundenen Konsequenzen für die Entstehung und die kosmologische Entwicklung von Aktive Galaxien und Galaxien im Detail zu untersuchen.

1.2 Voraussetzungen zur Durchführung des Vorhabens

Die Potsdamer Arbeitsgruppe hat unter der Leitung von Axel Schwope eine exzellente Arbeit geleistet. So haben sie sich bei der Analyse von Röntgendaten und der optischen Identifizierung von schwachen Röntgenquellen international viel Anerkennung und eine gute Expertise erworben. Die Potsdamer Arbeitsgruppe wird daher auch in Zukunft trotz des Wechsels des Antragssteller als Direktor am MPE Garching und des damit verbundenen Wechsels einiger Mitglieder der Gruppe wesentlich zur Leistungsfähigkeit des Astrophysikalischen Intituts Potsdam beitragen.

1.3 Planung und Ablauf

Schwerpunkte der Arbeiten zu Beginn des Vorhabens waren die detaillierte Auswertung und Publikation der ersten tiefen XMM-Newton Beobachtung im Gebiet des Lockman Holes sowie die ersten optischen Identifikationen des "Chandra Deep Field-South" Feldes mit Hilfe der spektroskopischer Beobachtungen mit dem FORS-Intrument an den VLT-Teleskopen sowie dem NTT-Teleskop auf LaSilla. Zur Unterstützung des Vorhabens konnten bereits 7 Nächte Beobachtungszeit am VLT und 6 Nächte am Keck-Teleskop eingeworben werden.

Des weiteren konnten die Publikationen zur optischen Identifizierung des "Ultra Deep ROSAT Survey" im Lockman Hole sowie zur kosmologischen Evolution der Leuchtkraftfunktion von röntgenselektierten Quasaren und aktiven Galaxien abgeschlossen werden. Im weiteren Verlauf des Vorhabens konnten nahezu 60% der Röntgenquellen des "Chandra Deep Field-South" Feldes anhand von VLT-Beobachtungen identifiziert werden (siehe Anhang).

1.4 Wissenschaftlicher Stand zu Beginn des Vorhabens

Tiefe Röntgendurchmusterungen haben ergeben, dass der kosmische Röntgenhintergrund (XRB) mehrheitlich auf die Akkretion von Materie auf supermassereiche Schwarze Löcher zurückzuführen ist. Der ROSAT-Satellit hatte ungefähr 70-80% des weichen Röntgenhintergrundes in einzelne Quellen aufgelöst, wobei die Mehrzahl der Quellen durch umfangreiche spektroskopische Beobachtungen mit dem Keck-Teleskop als Aktive Galaxienkerne (AGN) identifiziert wurde. Das vereinheitlichende Modell für AGNs ist weitestgehend akzeptiert. Die Physik des Schwarzen Loches, der Akkretionsscheibe, des Jets und des absorbierenden Toruses sind mit dem Sichtwinkel des Beobachters so verbunden, dass die scheinbar unvereinbaren Eigenschaften der einzelnen Typen von Aktiven Galaxienkernen erklärt werden können. Typ-1 Objekte (Quasare, Seyfert-Galaxien) zeigen direkt die Merkmale der zentralen Maschine ohne Absorption, wogegen Typ-2 Objekte dann auftreten, wenn die Sicht durch absorbierenden optisch sehr dichten Staub/Gas (z.B. in Form eines zirkumnuklearen Toruses in der Gröenordnung von einigen Parseks nach dem Standard AGN-Modell) verhindert ist. Tiefe Himmelsdurchmusterungen mit ROSAT haben hauptsächlich Typ-1 Objekte entdeckt. Das charakteristische harte Spektrum des Röntgenhintergrundes kann jedoch nur erklärt werden, wenn die Mehrzahl der AGNs im Universum stark absorbiert sind, also vom Typ-2 sind. Ein kritischer Bestandteil der Populationssynthesemodelle des Röntgenhintergrundes ist daher der groe Beitrag von stark absorbierten leuchtkräftigen AGNs, den sogenannten Typ-2 Quasaren. Laut Vorhersagen sollen sie schmale verboten Emissionslinien, eine starke harte Röntgenemission und eine hohe Equivalentbreite der Fe Ka-Linie aufweisen. ber viele Jahre wurde die Existenz solcher Objekte in Frage gestellt. Mit dem erfolgreichen Auffinden eines optisch absorbierten, sehr stark röntgenabsorbierten, leuchtkräftigen zentralen AGN in der Sternentstehungsgalaxie NGC 6240 konnte demonstriert werden, dass das Typ-2 QSO-Phänomen im harten Röntgenlicht aufgedeckt werden kann. Die unabsorbierte Röntgenleuchtkraft von NGC 6240 liegt dabei zwischen der von normalen Typ-1 Quasaren und der von Seyfert-Galaxien. Der gröte Anteil der Leuchtkraft wird jedoch durch verdeckendes Medium absorbiert und muss daher in der starken thermischen Staubkomponente im Mittleren- und Ferninfrarot re-emitiert werden.

Tiefe Himmelsdurchmusterungen im harten Röntgenband (2-10 keV) und deren vollständige, qualitativ hochwertige spektroskopische Identifizierung waren absolut notwendig, um die Erkennisse aus den ROSAT-Durchmusterungen über die Zusammensetzung des Röntgenhintergrundes und der kosmologischen Entwicklung seiner Konstituenten zu verifizieren und um weitere, wichtige Details zu ergänzen.

1.5 Zusammenarbeit mit anderen Stellen

Max-Planck-Institut für extraterrestrische Physik (J. Trümper, W. Voges, H. Fink): Analyse der Röntgendaten, ROSAT All-Sky Survey

Caltech (M. Schmidt): Optische Identifikationen mit Palomar und Keck-Teleskop

ESO Southern Observatory (R. Giacconi, P. Rosati, V. Mainieri): Tiefe Röntgendurchmusterungen

Universität Bologna (G. Zamorani): ROSAT und XMM Deep Survey

SAO Seletchuk (Y. Balega, S. Dodonov, S. Afanasiev, Neizvestny S.): Identifikationen 6m-Teleskop

Penn. State University (D. Schneider): Lockman Hole Deep Survey

Universität Padova (P. Rafanelli): Wechselwirkung und Galaxienaktivität

MSSL (K. Mason): RIXOS-Projekt

1.6 Mitarbeiter der Arbeitsgruppe

Mitarbeiter	Status	G/P	Projektbeteiligung
G. Hasinger	Projektleitung	G	wiss. Leitung, opt. Beob. Keck
J. Wambsganß	Wissenschaftler	G	Koordination Galaxienhaufen
A. Schwope	Wissenschaftler	P/G	opt. Beob., Catacl. Variable
I. Lehmann	Wissenschaftler	G	Röntgenanalyse, opt. Beob.
G.P. Szokoly	Wissenschaftler	P	optische/nah-infrarot Beob.
Y. Hashimoto	Wissenschaftler	G	Röntgenanalyse der Galaxienhaufen
M. Salvato	Doktorand	P	opt. Beobachtung, Wechselwirkung
D. Meinert	EDV-Wissenschaftler	G	Rechentechnik, Systembetreuung
K.-H. Böning	EDV-Technik	G	Datenprozessierung
M. Treyer	Post-Doc	G	Fluktuations- und Korrelationsanalyse
T. Miyaji	Post-Doc	G	Leuchtkraftfunktionen, ASCA Surveys

2 Ergebnisse

2.1 Wissenschaftliche Ergebnisse

Die tiefsten Röntgendurchmusterungen mit den neuen Chandra- und XMM-Newton-Satelliten haben erst kürzlich den gröten Teil des harten Röntgenhintergrundes in einzelne Quellen aufgelöst. Das "Hubble Deep Field-North" und das "Chandra Deep Field-South", zwei sehr detailliert untersuchte Himmelsregion in nahezu allen Wellenlängenbereichen, wurden mit dem Chandra-Satelliten mit Gesamtbelichtungszeiten von 2 Msec bzw. 1 Msec aufgenommen. Eine detaillierte Beschreibung der Ergebnisse aus der tiefen Chandra-Durchmusterung im "Chandra Deep Field-South" ist im Anhang dargestellt. Die erste tiefe Durchmusterung mit XMM-Newton (100 ksec Belichtungszeit) wurde in der Region des Lockman Holes durchgeführt, einem Gebiet, das mit ROSAT sowie in anderen Wellenlängenbändern gut studiert ist. Optische Spektroskopie mit den Keck-Teleskopen und dem VLT (in Arbeit) führte zu dem Resultat, dass die Mehrzahl der neuen Quellen wahrscheinlich intrinsisch absorbierte Typ-2 AGNs sind, exakt die durch die Hintergrundspopulationssynthese hervorgesagten Objekte. Unter den höchst interessanten neuen Ergebnissen aus diesen Durchmusterungen ist die Entdeckung verschiedener Beispiele der seit langem gesuchten Klasse von Typ-2 QSOs. In der 1 Msec "Chandra Deep Field-South"-Aufnahme haben wir den höchstrotverschobenen, derzeit bekannten Typ-2 AGN mit einer Rotverschiebung von 3.70 entdeckt, ein klassischer Typ-2 QSO (CDF-S 202). Die Quelle besitzt das härteste Röntgenspektrum bei hohen Rotverschiebungen. Die spektrale Energieverteilung von CDF-S weist eine bemerkenswerte Ähnlichkeit mit der SED von NGC 6240 auf. Ein weiterer Typ-2 QSO X174 wurde in der 100 ksec XMM-Newton-Aufnahme vom Lockman Hole gefunden wurde. Das Keck-Spektrum des Typ-2 QSOs wurde im enthält nur schmale Lya-, HeII- und C III]-Emissionslinien.

Das Chandra-Röntgenspektrum von CDF-S 202 hat nur 130 Photonen im 0.5-7 keV Energieband. Trotzdem konnte ein Anzeichen für eine groe absorbierende Säulendichte des neutralen Wasserstoffs von NH $\leq 10^{24-25}$ cm^{-2} festgestellt werden. Ein Restüberschuss an Photonen bei 1.4 keV ist konsistent mit der Existenz einer Eisen K-alpha Linie bei 6.4 keV Ruheenergie und einer Equivalentbreite von 1 keV. Dieses Resultat stimmt mit dem Absorptionsszenario überein, womit möglicherweise eine hochrotverschobene Fe K-alpha Linie detektiert wurde. In Abhängigkeit von der verwendeten Kosmologie und des Röntgentransfermodells kann von einer intrinsischen, absorptionskorrigierten Leuchtkraft von 10450.5 erg s-1 im 2-10 keV Band ausgegangen werden, wodurch unsere Quelle ein Beispiel für einen seit langem gesuchten Typ-2 Quasar ist. Die absorbierte Röntgenleuchtkraft der Quelle X174A im Lockman Hole beträgt 1043.5 erg s-1 im 0.5-2 keV Band. Das geringe Signal-zu-Rausch-Verhältnis des XMM-Newton-Spektrums von X174A ist mit einer starken intrinsischen Absorption von log NH¿ 22.0 ebenfalls konsistent mit einem Typ-2 Quasar. Auf Grundlage der Populationssynthesemodelle wird vermutet, dass 90% der durch ein Schwarzes Loch angetriebenen QSOs bei hoher Rotverschiebung diesem Objekttyp entspricht. Typ-2 Quasare sind im optischen jedoch extrem schwach.

In der tiefen ROSAT-Durchmusterung in der Himmelsregion des Lockman Hole wurde ein Galaxienhaufen mit einer interessanten hantelförmigen Röntgenmorphologie gefunden, die auf eine mögliche gravitative Wechselwirkung von zwei Galaxienhaufen hindeutet. Innerhalb der östlichen Röntgenstruktur befindet sich eine, durch eine Gravitationslinse abgebildete, Galaxie bei einer Rotverschiebung von 2.577. Keck-Beobachtungen der Quelle RXJ 105343+5735 haben die Existenz eines massereichen, hochrotverschobenen Galaxienhaufens bestätigt. Tiefe optische und Nah-Infrarotaufnahmen zeigen eine erhöhte Konzentration von Galaxien in beiden Röntgenregionen, im speziellen ist ein signifikanter berschuss von Galaxien mit einer Farbe von $R-K > 5$ festgestellt worden, ein typisches Merkmal von elliptischen Galaxien mit Rotverschiebungen z>1. Anhand neuer photometrischer Daten konnten die Rotverschiebungen von Mitgliedern des Galaxienhaufens genauer bestimmt werden. Ein Keck-NIRSPEC-Spektrum einer der hellen Zentralgalaxien der östlichen Röntgenstruktur zeigt eine schmale H-alpha-Emissionslinie bei 1.485 μm, woraus sich eine Rotverschiebung von 1.263 ableitet. Das Auffinden einer schmalen [O II]-Emissionslinie im Nah-Infrarotspektrum der Galaxie, die durch die Gravitationslinse abgebildet wurde, führte zur Bestätigung der Rotverschiebung von 2.577. Da eine zufällige räumliche berlagerung nicht wahrscheinlich ist, sowie die Farben der Galaxien in beiden Röntgenstrukturen konsistent sind, kann von einer Rotverschiebung von 1.26 für die Galaxien der westlichen Röntgenstruktur ausgegangen werden. Das System könnte daher ein Paar von Galaxienhaufen repräsentieren, das sich gerade im Prozess des Zusammenstosses befindet.

XMM-Newton Beobachtungen von RXJ1053.7+5735 mit einer Gesamtbelichtungszeit von 100 ksec wurden während der "Performance Verification Phase" aufgenommen. Zum ersten Mal konnte für einen so hochrotverschobenen Galaxienhaufen ein hochwertiges Röntgenspektrum gewonnen werden. Die Temperatur des Haufens von Tx=4.9 keV basiert auf einer simultanen Modellanpassung der Spektren aller EPIC-Kameras (pn+MOS). Der Wert der Metallizität wurde mit einer oberen Grenze von 0.62 der solaren Eisenhäufigkeit ermittelt. Anhand der Parameter der besten Modellanpassung haben wir eine bolometrische Leuchtkraft von Lbol=3.4 10^{44} erg/s abgeleitet. Die neue Haufentemperatur und die bolometrische Leuchtkraft sind konsistent mit einer schwachen bzw. keiner Entwicklung der Lbol - Tx-Relation bis zu Rotverschiebungen von z=1.3.

2.2 Wirtschaftliche Erfolgsaussichten

Das Vorhaben im Rahmen der astrophysikalischen Grundlagenforschung liefert naturgemäß keine direkten, wirtschaftlich verwertbaren Ergebnisse. Die Ergebnisse sind in erster Linien von besonderer Bedeutung für das Verständnis der physikalischen Grundgesetze und der Enstehung und Entwicklung des Universums. Hierbei bietet die Astrophysik die Möglichkeit Materie unter extreme Bedingungen, wie z.B. bei Temperaturen von einigen Millionen Grad Kelvin, zu untersuchen. Die daraus gewonnenen Erkenntnisse können in der Zukunft durchaus einen wirtschaftlichen Nutzen erbringen.

Durch das ständige Vordringen an die jeweiligen technologischen Grenzen gibt die Astrophysik immer neue Anstöße für die Entwicklung neuer Technologie und Fertigungmethoden, speziell im Bereich der Sensorik und der Materialentwicklung. Die Astrophysik gehört daher auf Grund ihrer hohen technologischen Leistungsfähigkeit zu den wichtigsten Standortfaktoren der Bundesrepublik Deutschland (siehe dazu den Bericht des BMBF zur technologischen Leistungsfähigkeit Deutschlands, 1998).

Die Entwicklung und Mission des deutschen Röntgensatelliten stellt dabei ein sehr gutes Beispiel für die Ausstrahlung wissenschaftlicher Anforderungen auf die Technologie und die wirtschaftliche Anwendung dar. Um die extrem glatten Oberflächen der komplizierten, asphärischen Glaskörper des ROSAT-Teleskops herzustellen, wurde von der Firma Carl Zeiss eine spezielle Technik zur Herstellung asphärischer Flächen und zur Super-Politur von Oberflächen entwickelt. Diese Technologie ist voll in den wirtschaftlich relevanten Produktionsprozess von hochgenauen asphärischen Objektiven zur UV-Photolitographie bzw. zum Schleifen von Brillengläsern eingeflossen.

Eine weiteres wichtiges Ergebnis ist der Wissenstranfer im Bereich der Entwicklung von Röntgendetektoren. So werden Analyseverfahren zur Struktur- und Mustererkennung aus astrophysikalischen Fragestellungen oder zum Studium von Phasenübergängen bei komplexen Plasmen in die Medizindiagnostik oder Ingenieurwissenschaften transferiert. Röntgendetektoren, die für ROSAT-, ARIXAS- und XMM-Newton-Teleskope entwickelt wurden, werden einer industriellen Verwertung, z.B. Strahlungsdosismonitoring zugeführt.

Die Erkenntnisse aus den tiefen Himmelsdurchmusterungen mit XMM-Newton und Chandra stellen gleichzeitig den Ausgangspunkt für die Planung zukünftiger Röntgenmissionen, z.B. ROSITA, XEUS der ESA oder Constallation-X der NASA, dar. Hierbei ergeben sich wieder neue Anforderungen an die Herstellung von sehr groß en leichtgewichtigen Röntgenspiegeln sowie die Entwicklung neuer Detektoren, die wiederum in der Röntgendiagnose oder Materialwirtschaft Anwendung finden.

2.3 Wissenschaftliche/technische Verwertung

Mit dem gegenwärtigen Vorhaben werden die intrumentellen Möglichkeiten der neuesten Generation von Röntgensatelliten sowie der für die Nachbeobachtung vorgesehenen bodengebundenen Observatorien, wie die Keck-, Subaru, und VLT-Teleskope, bis an die Grenze ihrer intrumentellen Leistungsfähigkeit ausgereizt. Die neu gefundenen, teilweise optisch extrem schwachen Gegenstücke der Röntgenquellen weisen schon jetzt auf die benötigte Leistungsfähigkeit der nächsten Generation von bodengebundenen Großteleskopen.

Tiefe Röntgendurchmusterungen und deren optische Identifikation können auf Grund des grossen Beobachtungsaufwands nur innerhalb von national und international eng verzahnten Koorperationsbeziehungen durchgeführt werden. Im vorliegenden Projekt gibt es einerseits eine internationale Zusammenarbeit zwischen verschiedenen wissenschaftlichen Institutionen, die jeweils mit verschiedenen Röntgenmissionen verbunden sind (Chandra, XMM-Newton), anderseits eine Zusammenarbeit mit verschiedenen Astronomieinstitutionen, die einen garantierten Zugang zu optischen Großteleskopen haben (KECK, VLT, Subaru).

3 Relevante Publikationen (seit 1999)

3.1 Referierte Zeitschriften

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Appendix: Main results

4 Introduction

Deep X-ray surveys indicate that the cosmic X-ray background (XRB) is largely due to accretion onto supermassive black holes, integrated over cosmic time. In the soft (0.5-2 keV) band more than 90% of the XRB flux has been resolved using 1.4 Msec observations with ROSAT[17] and recently 1-2 Msec Chandra observations [29, 4] and 100 ksec observations with XMM-Newton [18]. In the harder (2-10 keV) band a similar fraction of the background has been resolved with the above Chandra and XMM-Newton surveys, reaching source densities of about 4000 $\deg^{-2}$. Surveys in the very hard (5-10 keV) band have been pioneered using BeppoSAX, which resolved about 30% of the XRB [9]. XMM-Newton and Chandra have now also resolved the majority (60-70%) of the very hard X-ray background. Optical follow-up programs with 8-10m telescopes have been completed for the ROSAT deep surveys and find predominantly Active Galactic Nuclei (AGN) as counterparts of the faint X-ray source population [31, 23] mainly X-ray and optically unobscured AGN (type-1 Seyferts and QSOs) and a smaller fraction of obscured AGN (type-2 Seyferts). The X-ray observations have so far been about consistent with population synthesis models based on unified AGN schemes [6, 13], which explain the hard spectrum of the X-ray background by a mixture of absorbed and unabsorbed AGN, folded with the corresponding luminosity function and its cosmological evolution. According to these models, most AGN spectra are heavily absorbed and about 80% of the light produced by accretion will be absorbed by gas and dust [7]. However, these models are far from unique and contain a number of hidden assumptions, so that their predictive power remains limited until complete samples of spectroscopically classified hard X-ray sources are available. In particular they require a substantial contribution of high-luminosity obscured X-ray sources (type-2 QSOs), which so far have only scarcely been detected. The cosmic history of obscuration and its potential dependence on intrinsic source luminosity remain completely unknown. Gilli et al. e.g. assumed strong evolution of the obscuration fraction (ratio of type-2/type-1 AGN) from 4:1 in the local universe to much larger covering fractions (10:1) at high redshifts (see also [7]). The gas to dust ratio in high-redshift, high-luminosity AGN could be completely different from the usually assumed galactic value due to sputtering of the dust particles in the strong radiation field [15]. This might provide objects which are heavily absorbed at X-rays and unobscured at optical wavelengths.

After having understood the basic contributions to the X-ray background, the general interest is now focussing on understanding the physical nature of these sources, the cosmological evolution of their properties, and their role in models of galaxy evolution. We know that basically every galaxy with a spheroidal component in the local universe has a supermassive black hole in its centre [11]. The luminosity function of X-ray selected AGN shows strong cosmological density evolution at redshifts up to 2, which goes hand in hand with the cosmic star formation history [26]. While the comoving space density of optically and radio-selected QSO has been shown to decline significantly beyond a redshift of 2.5 [30, 33], the statistical quality of X-ray selected AGN high-redshift samples still needs to be improved [26]. The new Chandra and XMM-Newton surveys are now providing strong additional constraints here. Optical identifications for the deepest Chandra and XMM-Newton fields are still in progress, however a mixture of obscured and unobscured AGN with an increasing fraction of obscuration at lower flux levels seems to be the dominant population in these samples too [3, 29, 35, 36] (see below). Interestingly, first examples of the long-sought class of high-redshift, high-luminosity, heavily obscured active galactic nuclei (type-2 QSO) have been detected in deep Chandra fields [28, 35] and in the XMM-Newton deep survey in the Lockman Hole field [24]. In this paper we give an update on the optical identification work in the Chandra Deep Field South, which thanks to the efficiency of the VLT has progressed furthest among the deepest X-ray surveys.

5 The Chandra Deep Field South (CDFS)

The Chandra X-ray Observatory has performed deep X-ray surveys in a number of fields with ever increasing exposure times [27, 20, 12] and has completed a 1 Msec exposure in the Chandra Deep Field South (CDFS [29]) and a 2 Msec exposure in the Hubble Deep Field North (HDF-N [4]. The Megasecond dataset of the CDFS is the result of the coaddition of 11 individual Chandra ACIS-I exposures with aimpoints only a few arcsec from each other. The nominal centre of the CDFS is α=3:32:28.0, δ=-27:48:30 (J2000). This field was selected in a patch of the southern sky characterized by a low galactic neutral hydrogen column density $N_H = 8 \times 10^{19}\ cm^{-2}$ and a lack of bright stars [29]. In Figure 1, we show the colour composite Chandra image of the CDFS. This was constructed by combining images

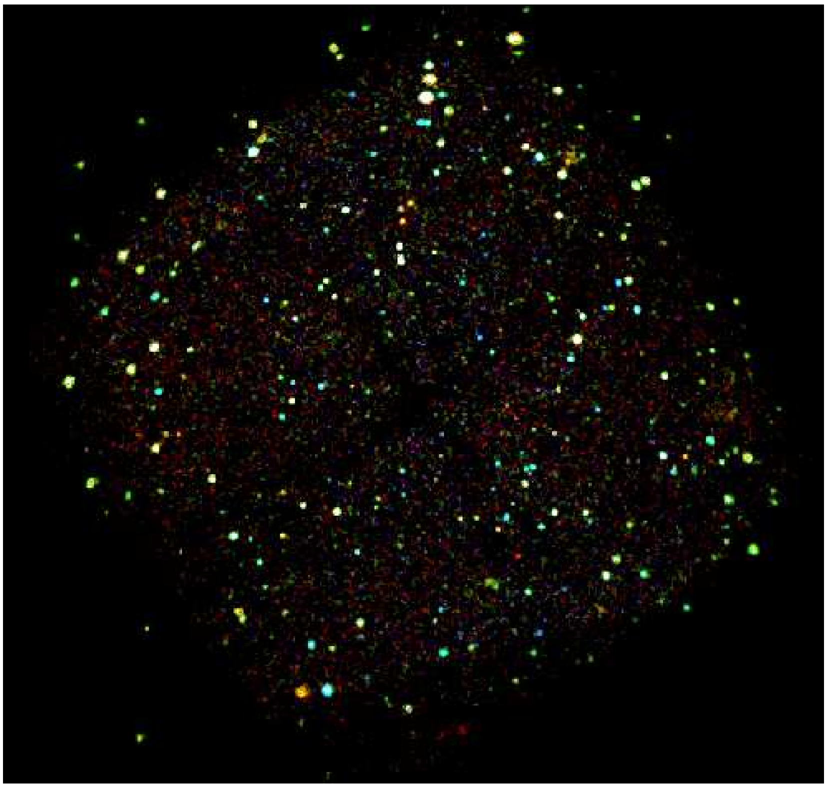

Figure 1: Color composite image of the Chandra Deep Field South of 940 ks (pixel size=0.984", smoothed with a (=1" Gaussian). The image was obtained combining three energy bands: 0.3-1 keV, 1-3 keV, 3-7 keV (respectively red, green and blue).

(smoothed with a Gaussian with $\sigma = 1''$ in three bands (0.3-1 keV, 1-3 keV, 3-7 keV), which contain approximately equal numbers of photons from detected sources. Blue sources are those undetected in the soft (0.5-2 keV) band, most likely due to intrinsic absorption from neutral hydrogen with column densities $N_H > 10^{22}\ cm^{-2}$. Very soft sources appear red. A few extended low surface brightness sources are also readily visible in the image. The CDFS was also observed with XMM-Newton for a total of $\sim$ 500 ksec in July 2001 and January 2002 in guaranteed observation time (PI: J. Bergeron). Due to high background conditions some data were lost and a total of $\sim$ 370 ksec has finally been accumulated [19].

6 Optical identifications in the CDFS

Our primary optical imaging was obtained using the FORS1 camera on the ANTU (UT-1 at VLT) telescope. The R band mosaics from this data cover 13.6'x13.6' to depths between 26 and 26.7 (Vega magnitudes). These data do not cover the full CDFS area and must be supplemented with other observations. The ESO Imaging Survey (EIS) has covered this field to moderate depths in several bands [2, 37]. The EIS data have been obtained using the Wide Field Imager (WFI) on the ESO-MPG 2.2 meter telescope at La Silla. Figure 2 shows Chandra X-ray contours in a selected area of the CDFS superposed on a deep BRK multicolour image. The positioning is better than 0.5" and we readily identify likely optical

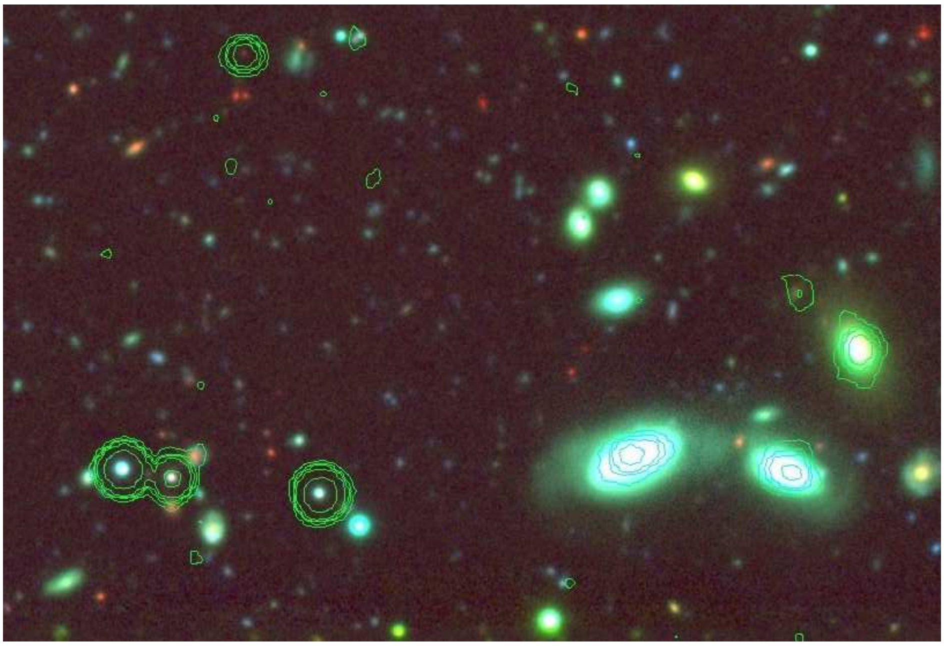

Figure 2: Cutout of a part of the CDFS. A deep FORS R-image has been combined with the EIS WFI B-image and the GOODS ISAAC K-image. X-ray contours are overplotted on the optical/NIR data. The image shows diffuse X-ray emission for the bright galaxies. The very red counterpart in the lower right is only visible in the deep GOODS K-band image (from [19]).

counterparts in 85% of the cases (78% for the shallower WFI data). Note the very red object in the lower right, which is only detected at K. Figure 3 shows the classical correlation between optical (R-band) magnitude and X-ray flux of the CDFS-objects. Generally the 0.5-2 keV flux is given, however, for Chandra sources not detected in the soft band, the 2-10 keV flux is given. Sources are marked according to their optical classification (see below). The Chandra data extend the previous ROSAT range by a factor of 40 in flux and to substantially fainter optical magnitudes. While the bulk of the type-1 AGN population still follows the general correlation along a constant f_X/f_{opt} line, the type-2 AGN cluster at higher X-ray to optical flux ratios. There is also a new population of normal galaxies showing up at significantly brighter optical magnitudes.

Optical spectroscopy has been carried out in 11 nights with the ESO Very Large Telescope (VLT) in the time frame April 2000 - December 2001, using deep optical imaging and low resolution multiobject spectroscopy with the FORS instruments with individual exposure times ranging from 1-5 hours. Some preliminary results including the VLT optical spectroscopy have already been presented [28, 29]. The complete optical spectroscopy will be published in [36]. Redshifts could be obtained so far for 169 of the 346 sources in the CDFS, of which 123 are very reliable (high quality spectra with 2 or more spectral features), while the remaining optical spectra contain only a single emission line, or are of lower S/N. For objects fainter than R=24 reliable redshifts can be obtained if the spectra contain strong emission lines. For the remaining optically faint objects we have to resort to photometric redshift techniques. Nevertheless, for a subsection of the sample at off-axis angles smaller than 8 arcmin we obtain a spectroscopic completeness of about 60%.

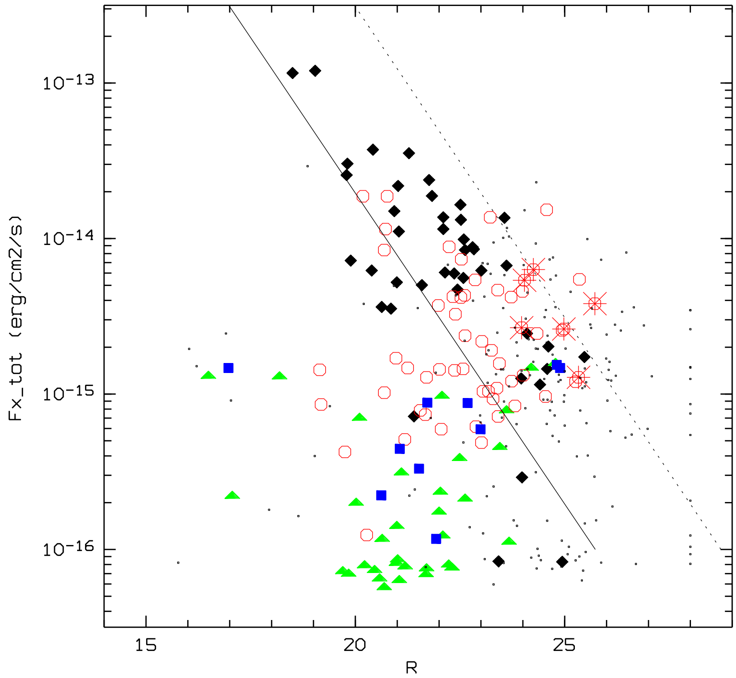

Figure 3: X-ray flux versus R-band magnitude for the CDFS-sources. Objects are coloured according to their X-ray/optical classification: filled black diamonds correspond to type-1 AGN, open red hexagons to type-2 AGN, green triangles to galaxies and blue squares to extended X-ray sources. The large asterisks indicates type-2 QSOs (see text). Small dots refer to spectroscopically unidentified CDFS sources, the brighter ones of which have photometric redshifts. Optically empty error circles have been plotted at R=28. The solid line corresponds to an X-ray to optical flux ratio of 1, the dashed line is at an optical limit 3 magnitudes fainter.

Type-1 AGN (Seyfert-1 and QSOs) can be often readily identified by the broad permitted emission lines in their optical spectra. Luminous Seyfert-2 galaxies show strong forbidden emission lines and high-excitation lines indicating photoionization by a hard continuum source. However, already in the spectroscopic identifications of the ROSAT Deep Surveys it became apparent, that an increasing fraction of faint X-ray selected AGN shows a significant, sometimes dominant contribution of stellar light from the host galaxy in their optical spectra, depending on the ratio of optical luminosity between nuclear and galaxy light [23]. If an AGN is much fainter than its host galaxy it is not possible to detect it optically. Many of the counterparts of the faint X-ray sources detected by Chandra and XMM-Newton show optical spectra dominated by their host galaxy and only a minority have clear indications of an AGN nature (see also [3]. In these cases, the X-ray emission could still be dominated by the active galactic nucleus, while a contribution from stellar and thermal processes (hot gas from supernova remnants, starbursts and thermal halos, or a population of X-ray binaries) can be important as well. Therefore X-ray diagnostics in addition to the optical spectroscopy can be crucial to classify the source of the X-ray emission. AGN have typically X-ray luminosities above 10^{42} $erg\ s^{-1}$ and power law spectra, often with significant intrinsic absorption[25]. Local, well-studied starburst galaxies have X-ray luminosities typically below 10^{42} $erg\ s^{-1}$ and very soft X-ray spectra. Thermal haloes of galaxies and the intergalactic gas in groups can have higher X-ray luminosities, but have soft spectra as well. Following [29], we show in Figure 6 the hardness ratio as a function of the luminosity in the 0.5-10 keV

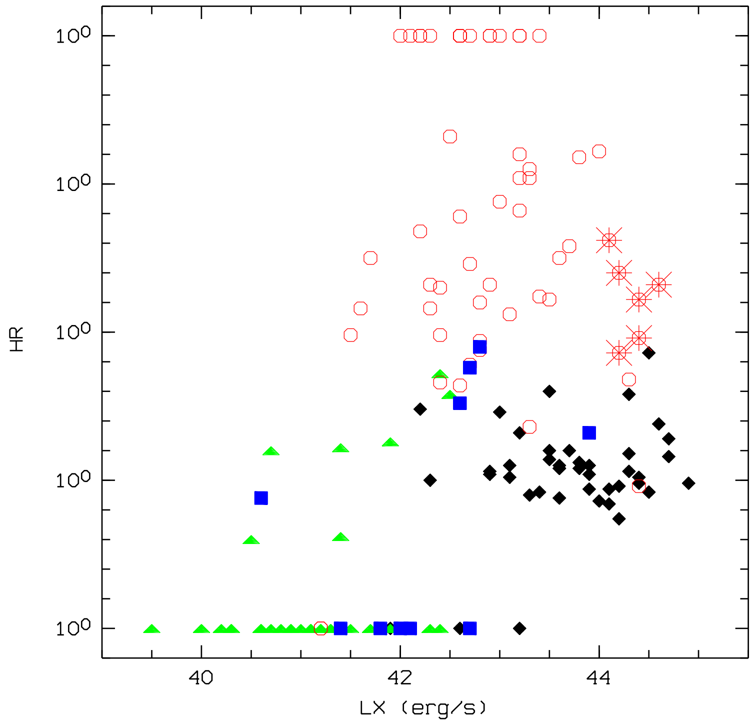

Figure 4: Hardness ratio versus rest frame luminosity in the total 0.5-10 keV band. Symbols as in Figure 3. A critical density universe with $H_0 = 50\ km\ s^{-1}\ Mpc^{-1}$ has been adopted. Luminosities are not corrected for possible intrinsic absorption.

band for 165 sources for which we have optical spectra and rather secure classification [36]. The hardness ratio is defined as HR = (H-S)/(H+S) where H and S are the net count rates in the hard (2-7 keV) and the soft band (0.5-2 keV), respectively. The X-ray luminosities are not corrected for internal absorption and are computed in a critical density universe with H_0=50 km s^{-1} Mpc^{-1}. Different source types are clearly segregated in this plane. Type-1 AGNs (black diamonds) have luminosities typically above 10^{42} $erg\ s^{-1}$, with hardness ratios in a narrow range around HR≈ -0.5. This corresponds to an effective $\gamma = 1.8$, commonly found in type-1 AGN. Type-2 AGN are skewed towards significantly higher hardness ratios (HR>0), with (absorbed) luminosities in the range 10^{41-44} $erg\ s^{-1}$. Direct spectral fits of the XMM-Newton and (some) Chandra spectra clearly indicate that these harder spectra are due to neutral gas absorption and not due to a flatter intrinsic slope [25]. Therefore the unabsorbed, intrinsic luminosities of type-2 AGN would fall in the same range as those of type-1's. In Figure 4, we also indicate the type-2 QSOs (asterisks), the first one of which was discovered in the CDFS [28]. In the meantime, more examples have been found in the CDFS and elsewhere (e.g. [35]). It is interesting to note that no high-luminosity, very hard sources exist in this diagram. This is a selection effect of the pencil beam surveys: due to the small solid angle, the rare high luminosity sources are only sampled at high redshifts, where the absorption cut-off of type-2 AGN is redshifted to softer X- ray energies. Indeed, the type-2 QSOs in this sample are the objects at $L_X > 10^{44}$ $erg\ s^{-1}$ and HR>-0.2. The type-1 QSO in this region of the diagram is a BAL QSO with significant intrinsic absorption. About 10% of the objects have optical spectra of normal galaxies (marked with triangles), luminosities below 10^{42} erg s^{-1} and very soft X-ray spectra (several with HR=-1), as expected in the case of starbursts or thermal halos. Those at $L_X < 10^{41.5}$ $erg\ s^{-1}$ and HR larger than -0.7 are at particularly low redshifts. However, a separate subset has harder spectra (HR>-0.5), and luminosities above 10^{41} $erg\ s^{-1}$. In these galaxies the X-ray emission is likely due to a mixture of low level AGN activity and a population of low mass X-ray binaries (see also [3]). Therefore the deep Chandra and XMM-Newton surveys detect for the first time the population of normal starburst galaxies out to intermediate redshifts [27, 12, 24]. These galaxies might become an important means to study the star formation history in the universe completely independently from optical/UV, sub-mm or radio observations.

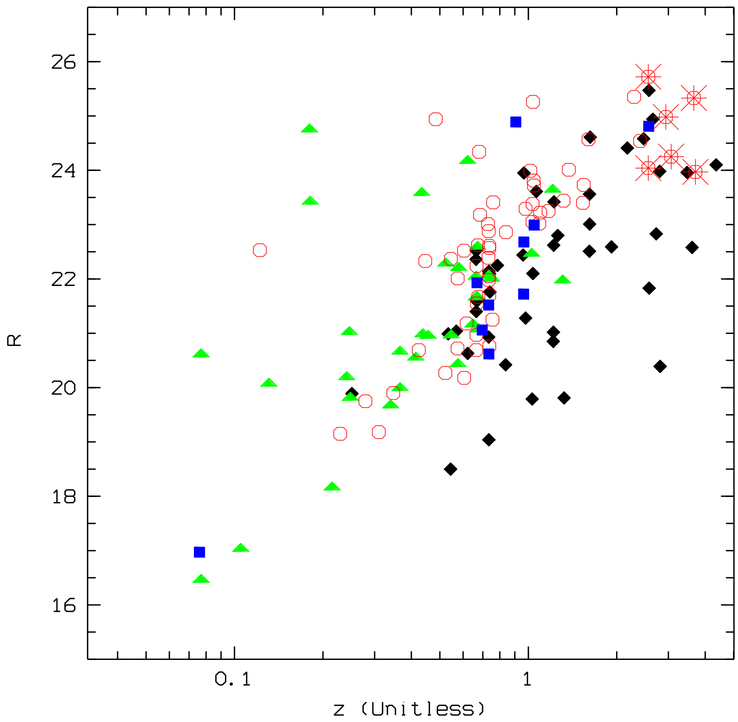

Figure 5: Left: Optical magnitudes as a function of redshift for the CDFS objects. Symbols are as in Figure 4. An accumulation of objects in two redshift bins around z=0.7 is due to a large scale structure in the CDFS[14].

7 The redshift distribution

Figure 5 shows the optical magnitudes of the spectroscopically identified CDFS sources as a function of redshift. There is a segregation between type-1 and type-2 AGN at high redshifts, most likely because the optical light from type-1 AGN contains a significant non-thermal contribution in addition to the host galaxy. Reliable redshifts can be obtained at the VLT typically for objects with R<25.5, however, some incompleteness already sets in around R=23. The CDFS has a spectroscopic completeness of about 60%, which is mainly caused by the fact that about 40% of the counterparts are optically too faint to obtain reliable spectra. Photometric redshift estimates of the remainder of the sources indicate a redshift distribution similar to the spectroscopic one. The completeness of 60% therefore allows us to compare the redshift distribution with predictions from X-ray background population synthesis models [13], based on the AGN X-ray luminosity function and its evolution as determined from the ROSAT surveys [26], which predict a maximum at redshifts around z=1.5. It is interesting to note, that contrary to these expectations, the bulk of the CDFS objects are found at redshifts below 1. The redshift distribution peaks at z$\sim$0.7, even if the normal star forming galaxies in the sample are removed. This clearly demonstrates that the population synthesis models will have to be modified to incorporate different luminosity functions and evolutionary scenarios for intermediate- redshift, low-luminosity AGN. In Figure 5 there is an interesting accumulation of redshifts in the range z=0.6-0.8. We have discovered two large-scale structures at redshifts z=0.66 and z=0.73, respectively, which are made up of type-1 and type-2 AGN as well as normal galaxies in roughly the same proportion as observed in the field. The objects in these redshift spikes are distributed across a large fraction of the field, so that they are probably sheet-like structures [14]. Both of them are also seen in the K-band galaxy survey selected in the same field [5] and also correspond to several X-ray clusters in the field. It will be interesting to study the correlation of active galaxies to field galaxies in these sheets and to try to determine the role that galaxy mergers play in the triggering of the AGN activity. Finally, there may be a relation between the surprisingly low redshift of the bulk of the Chandra sources, the existence of the sheets at the same redshift and the strongly evolving population of dusty starburst galaxies inferred from the ISO mid-infrared surveys [10]. By no means does the CDFS redshift distribution confirm the prediction by Haiman & Loeb [16], that a large number ($\sim$100) QSO at redshifts larger than 5 should be expected in any ultra deep Chandra survey. The highest redshift in the CDFS thus far is 3.7, while there are two objects at z=4.4 and z=5.2, respectively, in the HDF-N [4] and one QSO at z=4.5 in the Lockman Hole [32]. This suggests a cut-off of the X-ray selected QSO space density at high redshift.

8 Summary and outlook

Deep X-ray surveys have shown that the cosmic X-ray background (XRB) is largely due to accretion onto supermassive black holes, integrated over cosmic time. The findings are consistent with the notion that most larger galaxies contain black holes which have been active in the past. However, the characteristic hard spectrum of the XRB can only be explained if most AGN spectra are heavily absorbed [6]. Thus about 80-90% of the light produced by accretion must be absorbed by gas and dust clouds, which may reside in nuclear starburst regions that feed the AGN [7]. The star formation history has been determined in the last years based on optical and UV measurements [34]. However, deep submillimeter surveys with SCUBA have revealed the existence of a large population of hitherto undetected dust-enshrouded galaxies [21], which may provide the dominant contribution to the star formation rate at higher redshifts. The spectral shape of the X-ray background may be related to the dust obscuration of the far-infrared sources, which are believed to be the high-z equivalents of the ultra luminous IR galaxies (ULIRGs). For some ULIRGs the presence of heavily obscured AGN has been inferred by BeppoSAX (e.g. [38]). Therefore a relation between the faint X-ray and far-infrared source populations is expected. Indeed, a large fraction of the faint hard Chandra and XMM-Newton sources have infrared counterparts in deep ISOCAM images [8, 1] and the redshift distribution of faint X-ray sources and Mid-IR sources is similar (see above). The so-far deepest X-ray and SCUBA observations [20] did pick up only very few common objects. Even deeper X-ray images in conjunction with deep surveys at the peak wavelength of the far-infrared background e.g. with SIRTF, are therefore required. The Chandra Deep Field South has been selected as one of the deep fields in the SIRTF legacy programme "Great Observatories Origins Deep Survey" (GOODS), which will produce the deepest observations with the SIRTF IRAC instrument at 3.6-8μ and with the MIPS instrument at 24μ and together with the Chandra data provide the necessary depth and statistics to finally establish the FIR/X-ray relation. In addition to the data described here, a large number of supporting observations across a wide range of the electromagnetic spectrum are being carried out or planned. We have proposed to complement the already existing Chandra Megasecond observations with two 500 ksec ACIS-I pointings to homogenize and increase the exposure in the GOODS area to 2 Msec. Three small regions in the CDFS had already been observed with HST, which provides excellent morphology of the AGN host galaxies and photometry for the faintest optical counterparts [22]. The whole CDFS has already been covered by an extensive set of pointings with the new Advanced Camera for Surveys (ACS) in BVIz to "near HDF" depth. Following up the deep EIS survey in the CDFS, ESO has started a large program to image the GOODS area with the VLT to obtain deep JHKs images in some 32 ISAAC fields. The first imaging data covering the central 50 arcmin^2 have recently been made public. Optical spectroscopy across the whole field will be obtained with very high efficiency using VIRMOS on the VLT. The multiwavelength coverage of the field will be complemented by deep radio data from the VLA at 6 cm (already obtained) and ATCA at 20 cm. The CDFS/GOODS will therefore ultimately be one of the patches in the sky providing a combination of the widest and deepest coverage at all wavelengths and thus a legacy for the future.

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