ABSTRACT BOOK

ULTRA-LUMINOUS X-RAY SOURCES AND MIDDLE WEIGHT BLACK HOLES

a workshop organised by the
XMM-Newton Science Operations Centre
24 - 26 May 2010
ESA European Space Astronomy Centre
Villanueva de la Cañada
Madrid, Spain

Edited by
MARÍA DÍAZ TRIGO
XMM-Newton SOC, ESA

Scientific Organising Committee:

Richard Mushotzky (University of Maryland, USA) Chair
Didier Barret (CESR, Toulouse, France)
Aaron Barth (University of California at Irvine, USA)
Holger Baumgardt (University of Queensland, Australia)
Heino Falcke (Radboud University Nijmegen, The Netherlands)
Luis C. Ho (Canergie Observatories, Pasadena, USA)
Elmar Körding (Université Paris Diderot/CEA Saclay, France)
Stefanie Komossa (MPE Garching, Germany)
Mariano Méndez (Kapteyn Astronomical Institute, Groningen, The Netherlands)
Christian Motch (Observatoire de Strasbourg, France)
Juri Poutanen (University of Oulu, Finland)
Timothy Roberts (Durham University, UK)
Norbert Schartel (XMM-Newton Science Operations Centre, ESA) Co-Chair
Roberto Soria (MSSL, Dorking, UK)
Luca Zampieri (INAF-Osservatorio Astronomico di Padova, Italy)

Local Organising Committee:

María Díaz Trigo (Chair)
Michelle Arpizou
Matthias Ehle
Cristina Hernández
Nora Loiseau
Jan-Uwe Ness
Richard Saxton
Norbert Schartel
Martin Stuhlinger

Invited Speakers:

Tommaso Belloni (INAF, Osservatorio Astronomico di Brera, Italy)
Sean Farrell (University of Leicester, UK)
Chris Fryer (Los Alamos National Laboratory, New Mexico, USA)
Marat Gilfanov (MPA, Garching, Germany)
Jenny Greene (Princeton University, USA)
Shin Mineshige (Kyoto University, Japan)
Richard Mushotzky (University of Maryland, USA)
Manfred Pakull (Observatoire de Strasbourg, France)
Simon Portegies Zwart (Leiden Observatory, The Netherlands)
Roberto Soria (Mullard Space Science Laboratory, UK)
Tod Strohmayer (NASA/GSFC, Greenbelt, USA)
Marta Volonteri (University of Michigan, USA)

Contents

Chapter 1

Introduction

Introduction to the workshop

Mushotzky, Richard[1]
[1] *Department of Astronomy, University of Maryland*

I will present an introduction and over view of the 'ULX/middle weight black holes' observational and theoretical framework. In particular what we need to know about these objects, how we can obtain that information and why they are interesting (and perhaps important). I will try to set the background for the meeting and focus on the historical setting and analogs to better understood black holes and what we have learned so far. I will not come to any conclusions, but try to sketch out what I hope the workshop results will be.

Chapter 2

Topic 1: Observational characteristics

Black Hole states in external galaxies

Belloni, Tomaso[1]
[1] *INAF - Osservatorio Astronomico di Brera, Merate, Italy*

The past decade has seen considerable advancement in the field of galactic Black-hole binaries. This class is now populated by dozens of systems and their phenomenology, although still little understood, is now clear and classified in a small number of source states. These states are defined by a combination of spectral and timing properties which are easy to obtain from bright sources.

Thanks to the high throughput of XMM-Newton, these studies can now be applied to Ultraluminous X-Ray sources in external galaxies, although obviously limited by the lower statistics. A number of spectral and timing results have been presented suggesting different state identifications in a few ULXs. These are particularly important as they offer a unique window to their nature: whether super-Eddington stellar-mass or intermediate mass black holes.

I will outline the current observational status of galactic black hole binaries and review the current results on ULXs.

Unlocking the nature of ULXs using their X-ray spectra.

Gladstone, Jeanette[1] ; Roberts, Timothy[2] ; Done, Chris[2]
[1] *University of Alberta ;* [2] *University of Durham*

We explore the nature of ULXs through a detailed investigation of their spectral shape using some of the highest quality X-ray data currently available in the XMM-Newton public archives. The application of phenomenological models allows us to characterise the spectra of these objects, while the use of more physically motivated models enables us to explore the physical processes underlying these characteristics. Our results show that the spectra of these sources are fundamentally different to that of Galactic X-ray binaries, whilst the application of physical models indicates a more extreme version of the highest known luminosity state, the very high state. This indicates that in observing ULXs we are observing stellar-mass black hole binaries residing in a new 'ultraluminous' (super-Eddington) state, a state in which the theoretically predicted photosphere is observed and an increasingly powerful wind becomes dominant.

Optical properties of the ultraluminous X-ray source Holmberg IX X-1

Grise, Fabien[1] ; Kaaret, Philip[1] ; Pakull, Manfred[2] ; Motch, Christian[2]
[1] *University of Iowa, Iowa City, USA ;* [2] *Observatoire Astronomique, Strasbourg, France*

Holmberg IX X-1 is an archetypal ultraluminous X-ray source. Here we take an interest in the properties of the optical counterpart and of its stellar environment, using optical data coming from SUBARU/FOCAS, GEMINI/GMOS-N and HST/ACS. We depict an environment where the $V \sim 22.6$ spectroscopically identified optical counterpart is part of a loose cluster with an advanced age of 50 Myr. Consequently, the upper mass limit of individual stars in the association is about 7 M$\odot$ and likely corresponds to the mass of the donor star in the ULX. The fact that the counterpart is more luminous than the other stars of the association may be consistent with a non-negligible optical contribution of the accretion disk. This would explain the observed red and UV excess which point to a non-stellar object and resemble the situation encountered in low-mass X-ray binaries. This would be also consistent with the high-excitation emission lines that we see in the optical spectrum of the ULX : broad HeIIλ4686 and probably the NIII part of the Bowen complex have been identified which point to X-ray reprocessing in the accretion disk.

Optical Variability of the Ultraluminous X-ray source NGC 1313 X-2

Impiombato, Domenico[1] ; Zampieri, Luca[2] ; Falomo, Renato[3] ; Grise, Fabien[4] ; Soria, Roberto[5]
[1] *INAF, Astronomical Observatory of Padua, Padua, Italy ;* [2] *INAF, Astronomical Observatory of Padua, Padua, Italy ;* [3] *INAF, Astronomical Observatory of Padua, Padua, Italy ;* [4] *Observatoire Astronomique de Strasbourg, Strasbourg, France ;* [5] *Mullard Space Science Laboratory (UCL),Holmbury St. Mary,Dorking, United Kingdom*

We present archive ESO VLT+FORS1 and HST+WFPC2 photometric data of the Ultraluminous X-ray source NGC1313 X-2 analyzed with different photometric techniques. A preliminary analysis of the 20 HST observations confirmed the orbital modulation recently reported by Liu et al. (2009). The detected period is P=6.2+/-0.15, while the amplitude of the modulation is A=0.11+/-0.01. We will report also on the results of a similar analysis performed on the joint dataset of the HST+WFPC2 and ESO VLT+FORS1 data.

Properties Of The ULX Population In M82 From The 480ks GNOM82ES Observations

Kilgard, Roy[1] ; Roberts, Timothy[2] ; Jackson, Floyd[2]
[1] *Wesleyan University ;* [2] *Durham University*

We present an initial analysis of the ULX population in the star-forming galaxy M82 utilizing the new 480 ks Great NASA Observatories M82 Extended Survey (gnoM82es) observations as well as archival Chandra data to present long-term variability. The archival M82 observations consist of 9 pointings with the ACIS instrument (225 ks) and an additional 3 with the HRC (190 ks). In these archival observations, a total of 7 sources in excess of 5e38 erg/s were detected, only 3 of which exceed that luminosity in the gnoM82es observations. We also detect one additional source in excess of 5e38 erg/s. We present preliminary spectral and temporal analysis for these 8 sources. Though the spectrum of M82 X-1 is severely piled up in the observations obtained by the abstract deadline, we present preliminary spectral analysis using the pileup model to try to constrain its luminosity and general spectral shape.

Radio detections of off-nuclear ULX sources

Mezcua, Mar[1]
[1] *Max-Planck-Institute for Radioastronomy, Bonn, Germany*

Ultraluminous X-ray sources (ULXs) have typical luminosities well exceeding 10^{39} erg/s, suggesting either the presence of black holes larger than stellar mass black holes, or sources apparently radiating above the Eddington limit.

The fit of their X-ray spectra typically yield to disk temperatures much lower than Galactic black holes. This suggests that accretion disks in ULXs are large and cooler, implying intermediate mass black holes (Colbert & Mushotzky 1999) or even massive black holes (some of the ULXs in post-merger galaxies may harbor the elusive secondary supermassive black holes in binary black hole systems expected in such galaxies (Lobanov 2007)).

Radio observations of ULXs bear an excellent potential for uncovering the nature of these objects, by detecting and possibly resolving their compact radio emission, measuring its brightness temperature and spectral properties and assessing the physical mechanism for its production. However, no systematic studies of compact radio emission in ULXs have been done so far.

We present milliarcsecond-scale radio observations of a small sample of off-nuclear ULXs located within optical bright galaxies (Lehmer et al. 2006) to investigate whether they are intermediate mass black holes or supermassive black holes stripped off their accretion disks in the course of tidal interactions in post-merger systems.

Challenging times: A re-analysis of NGC5408 X-1

Middleton, Matthew[1] ; Roberts, Timothy[1] ; Done, Chris[1]
[1] *University of Durham*

Quasi-periodic oscillations (QPOs) are frequently observed in galactic black holes (GBHs) and have now been observed in a high mass accretion rate AGN. These prominent features are seen to scale tentatively with mass allowing crude mass estimates to be made, assuming the analogous feature is correctly identified. This can be achieved by accurately determining the position of the feature relative to breaks in the power spectrum, by flux spectral analysis and by more involved temporal analysis such as lag, rms and covariance spectra. We present a re-analysis of two deep XMM-Newton observations of the ultraluminous X-ray source NGC 5408 X-1, that strongly suggests that the ∼10 mHz signal may in fact be analogous to the Ultra Low Frequency QPOs seen in the most extreme GBHs. We discuss the consequences of this result for the presence of an intermediate-mass black hole in this source.

X-ray emission from star-forming galaxies

Mineo , Stefano[1] ; Gilfanov, Marat[1]
[1] *Max Planck Institute for Astrophysics*

We study the relation between the X-ray luminosity of compact sources and the SFR of the host galaxy. Our sample includes 38 galaxies for which a uniform set of *Chandra*, Spitzer and GALEX data has been collected. Our primary goals are (i) to obtain a more accurate calibration of the Lx-SFR relation and (ii) to understand the origin of the dispersion in the Lx-SFR relation observed previously. We also investigate the X-ray luminosity distribution function of HMXBs in order to determine more accurately its shape. In particular, we focus on the luminous part of the XLF to study the population of ULXs. To this end we extended our sample to include a number of relatively distant (but spatially resolved) galaxies characterized by high star-formation rates.

The supergiant optical counterpart of ULX P13 in NGC 7793

Motch, Christian[1] ; Pakull, Manfred [1] ; Grise, Fabien[2] ; Soria, Roberto[3]
[1] *CNRS, Universit de Strasbourg ;* [2] *University of Iowa ;* [3] *MSSL, University College London*

We have recently identified the optical counterpart of the ULX source P13 in the nearby spiral galaxy NGC 7793. The object is a V 20 mag star, ten times brighter than any other established counterpart of an ULX in nearby galaxies. Medium resolution optical spectroscopy recently carried out with the ESO-VLT reveals the presence of narrow high order Balmer, HeI and MgII absorption lines indicating a late B type supergiant mass donor. P13 might thus be in the short-lived high X-ray luminosity state associated to the transition of the donor to the supergiant phase. Non-nebular H alpha, H beta and HeII 4686 emission lines are also clearly seen superposed on the photospheric spectrum. In addition, we detect different patterns of radial velocity changes from the emission and absorption line systems over a month time interval. We will discuss the implications of our observations on the evolutionary status of this unique ULX and show how radial velocity variations can possibly constrain the mass of the accreting black-hole.

Radio counterparts to Ultraluminous X-ray sources

Perez-Ramirez, Dolores[1] ; Leon, Stephane[2] ; Castro-Tirado, Alberto[3]
[1] *Universidad de Jaen ;* [2] *Joint ALMA Observatory ;* [3] *Instituto de Astrofisica de Andalucia*

The number of ULX candidates has been growing extensively in the past years, being not longer considered a peculiar phenomenon, but quite common among galaxies. Although their existence has been observationally established, their physical nature remains unclear.

In certain cases, progress towards a better understanding of the ULX problem has been possible when a candidate radio counterpart has been detected. At radio wavelengths the extinction by the ISM is not an issue and the use of modern radio interferometers with better angular resolution and sensitivity, make possible to carry out searches for faint radio counterparts.

The cases for which such radio counterparts are available are not significant enough to establish statistically robust conclusion. Therefore, efforts to increase the number of radio detections could potentially lead to further evidence.

In this context, a goal in the present work has been to pursue a systematic search based on cross-identification of the VLA-FIRST radio sources and ULX candidates located in nearby galaxies in order to constrain and help to establish their physical nature.

We present in our study some interesting cases of positional coincidences for which further analysis has been carried out in terms of spectral index and variability properties.

Ten years of XMM-Newton observations of NGC 1313 X-2

Pintore, Fabio[1] ; Zampieri, Luca[2]
[1] *Astronomy Department, University of Padova,Padova I-35122, Italy ;* [2] *Astronomical Observatory of Padova,Padova I-35122,Italy*

We present a systematic re-analysis of the X-ray spectra of NGC1313 X-2, using the last ten years of XMM-Newton observations (14 observations). We fitted the continuum with a multicolor blackbody disk plus a comptonization model, describing the effects of an accretion disc plus an optically thick corona. We checked the consistency of this spectral model on the basis of the variability patterns of its spectral parameters. We also studied the RGS spectra of the longest observation available (123 ksec) in order to determine the chemical abundances in the local enviroment of NGC1313 X-2.

Chandra Observations of the ULX N10 in the Cartwheel Galaxy

Pizzolato, Fabio[1] ; Wolter, Anna[1] ; Trinchieri, Ginevra[1]
[1] *INAF - Osservatorio Astronomico di Brera*

The Cartwheel galaxy harbours more ULXs than any other galaxy observed so far, and as such it is a particularly interesting target to study them. We present three Chandra observations of the brightest ULX (N10) in the Cartwheel galaxy, in light of the current theoretical models. For each model we derive the relevant spectral parameters. Based on self-consistency arguments we can interpret N10 as an accreting binary system powered by a $\sim 100 M_{\odot}$ black hole. A young supernova strongly interacting with its surroundings is a likely alternative, that can be discarded only with the evidence of a flux increase from future observations.

New observations of ULX supershells, and their implications

Russell, David[1] ; Yang, Yi-Jung[1]
[1] *University of Amsterdam*

New optical narrowband imaging observations of the fields of several ULXs are presented. Known supershell nebulae are associated with a number of these ULXs, which we detect in emission lines filters such as [S II], He II, [O II] and [O III]. A few new nebulae are discovered, which are candidate ULX-powered supershells. The morphologies and emission line fluxes of these nebulae are then used to infer the properties of the emitting gas, which gives clues to the energising source (photoionization and/or kinetic shock-excitation, both likely from the ULX). Studies of supershells powered by ULXs can help to constrain the nature of ULXs themselves, such as the isotropy of the X-ray emission and the strength of their outflows.

ULX accretion states

Soria, Roberto[1]
[1] *MSSL (University College London)*

"Canonical" BH accretion states have been defined on the properties of Galactic BHs. The basic ingredient is the clear dychotomy between low/hard state—characterized by a hot Comptonizing medium, geometrically thicker inflow, collimated jet—and high/soft state—characterized by a thin, radiatively efficient, thermal disk, no jet and a well-tested relation between BH mass, inner-disk temperature and disk luminosity. A similar low/hard versus high/soft classification has even been applied to AGN. However, the problem with ULXs is that they do not behave like that. Very few (if any) ULXs have been seen to switch between the canonical low/hard and high/soft states. Most of the time, their 1-10 keV spectra are dominated by a moderately hard, broad, slightly curved component (with a few exceptions worth discussing). Forcing ULXs to belong to either canonical state produces erroneous estimates of their masses. That leaves us with a lot of unanswered questions. Why do they behave differently? (speculation: probably because of different properties of the matter inflow, rather than a different BH mass). If the inflow never collapses to a thin disk, can ULXs always have a steady jet, even at near-Eddington accretion rates? Are there Galactic BHs that behave like ULXs? Do AGN behave like ULXs?

An XMM-Newton and Chandra study of a small sample of the most luminous ULXs

Sutton, Andrew[1] ; Roberts, Timothy[1] ; Walton, Dominic[2]
[1]*Department of Physics, Durham University, Durham, UK ;* [2]*Institute of Astronomy, University of Cambridge, Cambridge, UK*

We present a sample of 10 extreme-luminosity candidate ultraluminous X-ray sources ($L\_X > 5\times10^{40}$ erg s^{-1}), all located within 100 Mpc, identified from a cross-correlation of the RC3 catalogue of galaxies with the 2XMM catalogue. Five of the sample have also been observed by *Chandra*. Of the 10 sources, seven reside in the disc or arms of spiral galaxies, and the remaining three are close to large elliptical galaxies. Unlike many less luminous ULXs, high levels of temporal variability on short (ks) and long (year) timescales are observed. Long term spectral variability is also evident in some sources. In one case, we use archival *Chandra* data to demonstrate that a hyperluminous X-ray source candidate identified by *XMM-Newton* is actually resolved into multiple point sources at high spatial resolution, but note that the other candidates remain unresolved under *Chandra's* intense scrutiny.

The Demographics of Ultraluminous X-ray Sources

Swartz, Douglas[1] ; Soria, Roberto[2] ; Tennant, Allyn[1]
[1]*NASA/MSFC ;* [2]*MSSL/UCL*

Results of recent statistical studies of the population of Ultraluminous X-ray sources will be presented including the outcome of a complete survey of 140 nearby galaxies. The following questions about ULXs and their environments will be addressed: Are ULXs associated with young star-forming regions and massive young clusters? What is the rate of ULXs? Do ULXs occur in the halos of galaxies? Do ULXs occur in dwarf galaxies? Is there an upper limit to the luminosity of ULXs?

Morphological Spectral Properties of Hot Gas and LMXBs in 3 Early-Type Galaxies

Vagshette, Nilkanth[1] ; Patil, Madhav[2]
[1]*Research student, S.P.S., SRTM, University, Nanded, India ;* [2]*Reader, S.P.S., SRTM, University, Nanded, India*

We present detailed analysis of morphological and spectral properties of hot gas and LMXBs in 3 nearby early-type galaxies (NGC 5866, NGC 1404, NGC 4125). The X-ray emission is mainly composed of a central-point like nucleus; point sources that are likely low mass X-ray Binaries (LMXBs) and diffuse hot gas. The spectra of the diffuse emissions are well fitted by thermal emission from hot gas with a global temperature of 0.36 0.62 keV and it decrease with increasing radius. The Chandra data for all resolved sources in different galaxies provide clear evidence for hard emission component, which can be parametrized by power-law model with photon indices in the range $\gamma \approx 1.84$ 1.93. Using standard β model the radial distribution of the diffuse gas based on the surface brightness distribution in the soft band (0.3 1.5 keV), we find core radius ranging from $r\_c \approx 6.7$ 9.25 arcsec and $\beta \approx 0.47$ 0.72.

We have also found the correlation between near-IR, Optical and X-ray observations with a view to established a link between hot gas and other phases of ISM in early-type galaxies.

A Large Catalogue of Ultraluminous X-ray Source Candidates in Nearby Galaxies

Walton, Dominic[1] ; Gladstone, Jeanette[2] ; Roberts, Timothy[2] ; Fabian, Andy[1]
[1]*Institute of Astronomy, University of Cambridge, UK ;* [2]*Department of Physics, University of Durham, UK*

Since their discovery, Ultraluminous X-ray sources (ULXs) have attracted attention due to their combination of extreme luminosities and extra-nuclear locations. However, they are a fairly rare phenomenon, and attempts to investigate the general properties of the population have been hindered by a relative lack of known sources.

Here, we present a large catalogue of ULX candidates including 655 detections of 475 discrete sources, based on the 2XMM Serendipitous Survey. To demonstrate the potential of such a resource, we present some scientific analysis of this population, focussing on the spectral turnover seen, often at $\sim$6 keV, in the highest quality ULX data. We also demonstrate how the recent reflection and Comptonisation interpretations of this feature may be distinguished observationally in the future, specifically for one previously unanalysed source with high quality data.

ULXs in NGC2276

Wolter, Anna[1] ; Mapelli, Michela[2] ; Ripamonti, Emanuele[2] ; Pizzolato, Fabio[1]
[1] *INAF-OABrera, Milano, Italy ;* [2] *Universita' Milano Bicocca, Milano, Italy*

NGC 2276 is an interacting spiral galaxy in which one ULX was proposed based on XMM-Newton data. It belongs to the NGC 2300 group, which might contribute to its lopsided appearance and manifest activity (eg. a large number of SNe). According to recent theoretical models (Mapelli, Colpi & Zampieri 2009), the high star formation rate (6.0 Msol/yr) of NGC2276 might be at odds with the small number of observed ULXs. We analyzed recent Chandra data where the previously known ULX is resolved in a number of sources. In the whole galaxy we detect 17 sources, of which at least 6 are at the ULX level. We will present preliminary results of this investigation, and the XLF of the galaxy and we will discuss shortly the metallicity/ULX relationship.

A statistical study of long-term variabilities of ultraluminous X-ray sources

Yoshida, Tessei[1] ; Ebisawa, Ken[1] ; Matsushita, Kyoko[2] ; Tsujimoto, Masahiro[1]
[1] *ISAS/JAXA ;* [2] *Tokyo University of Science*

Variable ultraluminous X-ray sources (ULXs), which are considered to be black hole binaries (BHBs), are known to show transitions between two states with different spectral shapes: power-law (PL) and convex-shaped. Similarly, Galactic BHBs are known to show transitions among four states: the low-hard state (PL-like), the high-soft state (convex), the very high state (PL-like), and the apparent standard state (convex). The relation between the ULX states and the Galactic BHB states is still unclear due mainly to less well-known temporal behaviors of ULXs.

We report a systematic X-ray spectral study of ULXs within 40 Mpc using the archived data from about 800 Chandra observations spanning 10 years. In order to compare with the Galactic BHB states, we tried applying a PL, a multi-color disk black body (MCD; convex shape), and a slim-disk model to all the ULX spectra.

In 10^{37} to 10^{41} erg/s, we found several apparent peaks in the luminosity distribution of the samples, indicating several distinct states. Based on best-fit parameters of each state, we discuss the nature of these states of ULXs and compare them with Galactic BHBs.

Low Mass X-ray Binaries in Globular Clusters in Nearby Galaxies

Zhang, Zhongli [1] ; Gilfanov, Marat[1] ; Voss, Rasmus[2] ; Sivakoff, Gregory[3] ; Kraft, Ralph[4] ; Brassington, Nicola[4] ; Kundu, Arunav[5]

[1] *Max-Plank-Institute for Astrophysics, Garching, Germany ;* [2] *Max-Plank-Institute for Extraterrestrial Physics, Garching, Germany ;* [3] *Virginia University, USA ;* [4] *Harvard Smithsonian Center for Astrophysics, USA ;* [5] *Michigan State University, USA*

We studied low mass X-ray binaries in globular clusters (GC-LMXBs) in eight galaxies (The Milky Way, M31, M81, Centaurus A, Maffei 1, NGC 3379, NGC 4697 and NGC 4278) to a limiting luminosity of e35 erg/s. 188 GC-LMXBs were found, which allowed us to construct a combined luminosity function with reliable statistics. Compared with the combined luminosity function of LMXBs in field, a deficit of GC-LMXBs below approximately e36 erg/s was confirmed. This indicates different formation histories of GC-LMXBs and field LMXBs.

Chapter 3

Topic 2: Evidence for intermediate mass black holes

An upper limit on the mass of the central black hole of NGC 6388

Cseh, David[1] ; Kaaret, Philip[2] ; Corbel, Stephane[1] ; Kording, Elmar[1] ; Coriat, Mickael[1] ; Tzioumis, Anastasios[3] ; Lanzoni, Barbara[4]
[1] *CEA Service d'Astrophysique & Universite Paris Diderot, France ;* [2] *Dept. of Physics and Astronomy, University of Iowa, Iowa City, US ;* [3] *CSIRO, ATNF Epping, New South Wales, Australia ;* [4] *Universita' degli Studi di Bologna, Dipartimento di Astronomia Bologna, Italy*

We present the results of deep radio observations with the Australia Telescope Compact Array (*ATCA*) of the globular cluster NGC 6388. We show that there is no radio source detected (with a r.m.s. noise level of 27 μJy) at the cluster centre of gravity or at the locations of the any of the *Chandra* X-ray sources in the cluster. Based on the fundamental plane of accreting black holes which is a relationship between X-ray luminosity, radio luminosity and black hole mass, we place an upper limit of $\sim$1500 M_$\odot$ on the mass of the putative intermediate-mass black hole located at the centre of NGC 6388. We discuss the uncertainties of this upper limit and the previously suggested black hole mass of 5700 M_$\odot$ based on surface density profile analysis.

Exploring the Nature of the Brightest Hyper-luminous X-ray Source

Farrell, Sean[1] ; Webb, Natalie[2] ; Wiersema, Klaas[1] ; Barret, Didier[2] ; Maccarone, Tom[3] ; Godet, Olivier[2] ; Servillat, Mathieu[4] ; Oates, Sam[5] ; Heywood, Ian[6]
[1] *University of Leicester, UK ;* [2] *CESR, France ;* [3] *University of Southampton, UK ;* [4] *Harvard-Smithsonian CfA, USA ;* [5] *MSSL, UK ;* [6] *University of Oxford, UK*

The small subset of hyper-ULXs with luminosities in excess of 1E41 erg/s are hard to explain without the presence of an intermediate mass black hole, as significantly super-Eddington accretion and/or very small beaming angles are required. The recent discovery of the most luminous ULX with a record breaking luminosity of 1E42 erg/s in the galaxy ESO 243-49 therefore currently provides some of the strongest evidence for the existence of intermediate mass black holes. This ULX is an order of magnitude brighter than the other hyper-ULXs, and exhibits X-ray spectral variability similar to Galactic stellar mass black hole X-ray binaries. I will present here a review of the current state of knowledge on this intriguing source and will outline the results of multi-wavelength studies from radio to gamma ray wavelengths. I will also present imaging and spectroscopy of the recently identified optical counterpart that we have obtained with the VLT. These results continue to support an intermediate mass black hole in excess of 500 Msun.

ULXs and Evidence for Two IMBHs in M82

Feng, Hua[1]
[1] *Tsinghua University*

M82 contains two of the most interesting ultraluminous X-ray sources (ULXs) in nearby galaxies, X41.4+60 and X42.3+59. Recently using joint Chandra and XMM-Newton observations, we have revealed evidence for intermediate mass black holes in these sources. For X41.4+60, the previously known quasi-periodic oscillations (QPOs) disappeared and the source was firmly identified in the thermal dominant state; a black hole of 200-800 solar masses with nearly maximal spin is required to interpret the data. For X42.3+59, mHz QPOs were discovered suggesting the presence of a 10^4 solar mass black hole. We also identified a third ULX in M82.

Analysing the optical imprints of an elongated ULX in an interacting galaxy pair

Fuentes-Carrera, Isaura[1] ; Rosado, Margarita[2] ; Flores, Hector [3] ; Borissova, Jordanka[4]
[1] *Escuela Superior de Fisica y Matematicas-IPN, Mexico City, Mexico ;* [2] *Instituto de Astronomia-UNAM, Mexico City, Mexico ;* [3] *Observatoire de Paris-Meudon, Meudon, France ;* [4] *Universidad de Valparaiso, Valparaiso, Chile*

We present observations of the extended optical counterpart of a bright, elongated ULX in the interacting galaxy pair NGC 5953/54 using the FLAMES-GIRAFFE integral field spectrograph on the VLT.

The spectroscopical and spatial information of the surroundings of this ULX are analysed in order to determine the nature of the source. The study of the kinematics of the surrounding gas, the detection of any asymmetries in the distribution of the ionized gas, and the nature of this ionization, are used to distinguish between several possible scenarios: beamed emission from a stellar-mass black hole binary, an intermediate-mass black hole associated with a young stellar cluster, or an extremely energetic supernova remnant.

The scaling of X-ray variability with luminosity in ULX sources

Gonzalez-Martin, Omaira[1] ; Papadakis, Iossif[1] ; Reig, Pablo[1] ; Zezas, Andreas[1]
[1] *Department of Physics, University of Crete*

ULXs could be the missed population of accreting objects with black-hole (BH) masses between Galactic BHs (GBHs) and supermassive BH (SMBHs): the intermediate mass BHs (IMBHs). However, their true nature is still unclear. We have investigated the relationship between X-ray variability amplitude and luminosity for a sample of 14 bright ULXs with XMM-Newton/EPIC data (Gonzalez-Martin et al.2010 to be submitted). We determined the normalized excess variance in the 2-10keV light curves together with the intrinsic luminosity L(2-10keV). We have compared this relationship to that found for AGN. Our main results are: (1) A significant evidence that the variability amplitude in ULXs decreases with increasing the L(2-10keV) and (2) for a given luminosity, the variability amplitude of ULXs is significantly smaller than that expected from a simple extrapolation of the AGN correlation to lower luminosities. We tested in which conditions ULXs could be 'scale-down' version of AGN (i.e. same shape on the power density spectra (PSD), same efficiency of the mass-to-energy conversion, and same X-ray-to-bolometric luminosity conversion). We concluded that they could be consistent with AGN if the PSDs show a second break and BH masses and accretion rates range M(BH)=5000-10000M$\odot$ and $\dot{m}$(Edd)=0.05-0.2, respectively.

Low-mass Black Holes in Galaxy Centers

Greene, Jenny[1] ; Ho, Luis[2] ; Barth, Aaron[3]
[1] *Princeton University ;* [2] *Carnegie Observatories ;* [3] *UC Irvine*

I review the search for 'low-mass' (i.e. 10^4-10^6 M_sun) black holes in the centers of galaxies. I focus predominantly on the use of nuclear activity to locate black holes, and discuss the resulting view of black hole demographics in low-mass galaxies. In order to compare these active black holes with ULXs, I also discuss their radiative properties. I conclude with future prospects to more firmly establish the true space density of low-mass black holes and extend our searches to even smaller galaxies.

A bright off-nuclear X-ray source: a recoiling SMBH?

Jonker, Peter[1,2] ; Torres, Manuel[2] ; Fabian, Andy[3] ; Heida, Marianne[4] ; Miniutti, Giovanni[5] ; Pooley, Dave[6]

[1] *SRON, Netherlands Institute for Space Research ;* [2] *Harvard-Smithsonian Center for Astrophysics ;* [3] *Institute of Astronomy ;* [4] *Utrecht University ;* [5] *LAEX, Centro de Astrobiologia ;* [6] *Astronomy department, University of Wisconsin*

We report the discovery of a peculiar X-ray source with a position 3.6±0.2" off-nuclear from an SDSS DR7 z=0.0447 galaxy. The 3.6" offset corresponds to 3.2 kpc at the distance of the galaxy. The 0.3–8 keV X-ray flux of this source is 5×10^{-14} erg cm-2 s-1 and its 0.3–8 keV luminosity is 2.2×10^{41} erg cm-2 s-1 (2.7×10^{41} erg/s; 0.5–10 keV) assuming the source belongs to the associated galaxy. We find a candidate optical counterpart in archival HST/ACS g′–band observations of the field containing the galaxy obtained on June 16, 2003. The observed magnitude of $g' = 26.4 \pm 0.1$ corresponds to an absolute magnitude of −10.1. We discuss the possible nature of the X-ray source and its associated candidate optical counterpart and conclude that the source is either a very blue type IIn supernova, a ULX with a very bright optical counterpart or a recoiling super-massive black hole.

Timing of millisecond pulsars as a tool for IMBH searching in globular clusters

Larchenkova, Tatiana [1] ; Lutovinov, Alexander[2]

[1] *Astro Space Center P.N.Lebedev Physical institute ;* [2] *Space Research Institute (IKI)*

We consider the possibility of the detection of intermediate mass black holes (IMBH, $10^3 - 10^4 M\_Sun$), whose presence in centers of some globular clusters is assumed from optical and infrared observations, using the precise timing of pulse arrival times of known millisecond pulsars in globular clusters. For several of them, located mostly close to centers of clusters, the expected time delays of their radiation in the gravitational filed of the central black hole are calculated. It is shown that the detection of such a delay by current instruments can be possible only for the mass of central object $\geq 10^4 M\_Sun$ and only for 1 or 2 globular clusters. We also considered the influence of the delay on changes of pulse period and its first derivative and shown that it will be negligible in a comparison with the current accuracy of their measurements. Nevertheless, in a future, with the progress in the observational instruments and technique, this method can become one of a few direct observations of IMBHs.

X-ray Variability of ULXs and the Mass of NGC 5408 X-1

Strohmayer, Tod[1]
[1] *NASA/Goddard, Greenbelt, MD USA*

Several of the brightest ULXs now have detections of characteristic variability timescales in the X-ray; including quasiperiodic oscillation and power spectral break frequencies. The best example at present is NGC 5408 X-1, which has shown X-ray timing and spectral behavior closely analogous to that observed in Galactic, stellar mass black holes, but at systematically higher luminosities and longer timescales. I will present recent XMM-Newton observations of X-1 that reveal a QPO frequency – spectral index relationship consistent with that seen in stellar-mass black hole systems of known mass. I will show that extension of the frequency – spectral index scaling relationship from the stellar-mass systems to X-1 suggests that it harbors an intermediate mass black hole. I will also present the results of regular, ongoing monitoring of X-1 with Swift, including the discovery of an 113 day periodicity that is likely the orbital period of the black hole binary.

Fingerprints of Intermediate Mass Black Holes in Globular Clusters

Trenti, Michele[1]
[1] *University of Colorado*

Globular clusters appear the best place to search for Intermediate Mass Black Holes (IMBHs), but no definitive observational evidence for their existence has been found. I will discuss the methods commonly used to search for IMBHs in globular clusters, mainly based on the IMBH impact on the cluster dynamics or brightness profile. Then I will present a novel technique for collisionally relaxed systems: the measure of the mass segregation profile. In fact, the evolution of a star cluster is strongly influenced by the presence of a central IMBH, as dynamical interactions within the core prevent the development of strong mass segregation. Our results are based on a large set of direct N-body simulations of star clusters that include single, binary stars and IMBHs. We compared the simulations to the mass segregation profiles of NGC 2298 and of M10 (NGC 6254). No IMBH with $M > 300\ M\odot$ is present in NGC2298 at 3σ. M10 does instead show less mass segregation than expected for single-stars only, thus this cluster represents a reasonable candidate for proper-motion follow-up. Similar measurements will be accessible in the near future for several tens of globular clusters thanks to archival HST data.

Acquisition of radial velocity curves of ULXs with GTC

Vilardell, Francesc[1] ; Casares, Jorge [2] ; Negueruela, Ignacio[1] ; Shahbaz, Tariq[2] ; Herrero, Artemio[2]

[1] *DFISTS, Universitat d'Alacant ;* [2] *Instituto de Astrofsica de Canarias*

The nature of Ultra-luminous X-ray sources (ULXs) in nearby galaxies is highly controversial: are they the long-sought intermediate mass black holes or a new state of stellar-mass black hole X-ray binary? Only radial velocity studies can unambiguously solve this puzzle. We have granted and guaranteed time with GTC to observe two of the brightest ULXs ($B < 22$ mag) accessible to GTC: NGC 5204 X-1 and Holmberg II X-1. The radial velocity curves of the ULXs companion stars obtained through long-slit spectroscopy with OSIRIS can settle the debate on whether ULXs contain a $\sim$100–1000 M$\odot$ black hole or not.

Chapter 4

Topic 3: Physics of accretion

Hydrodynamical Wind on a Magnetized ADAF With Thermal Conduction

Abbassi, Shahram [1] ; Ghanbari, Jamshid [2]
[1] *Damghan University of Basic Sciences, Damghan, Iran ;* [2] *Ferdowsi university of Mashhad, Mashhad, Iran*

We examine the effects of a hydrodynamical wind on the advection dominated accretion flows with thermal conduction in the presence of a toroidal magnetic field under a self-similar treatment. The disk gas is assumed to be isothermal. For a steady state structure of such accretion flows a set of self similar solutions are presented. The mass-accretion rate $\dot{M}$ decrease with radius r as $\dot{M} \propto r^{s+\frac{1}{2}}$, where s is an arbitrary constant. We show that existence of wind will lead to enhance of accretion velocity. The cooling effects of outflows or winds is noticeable and should be taken into account for calculating energy spectrum of ADAFs. Increasing of the effect of wind decrease the temperature of disk, because of energy flux which are taking away by the winds.

Relativistic X-ray disk reflection in Ultra-Luminous X-ray sources

Caballero-Garcia, Maria D.[1]
[1] *Institute of Astronomy, Cambridge (UK)*

A model based on relativistic disc reflection has proved to be successful in modeling the best XMM-Newton spectra of Ultra-luminous X-ray sources. A spectral drop is apparent in the data of all the sources at energies 6-7keV. The drop is interpreted here in terms of relativistically blurred ionized reflection from the accretion disc. A soft excess is also detected from these sources [as usually found in the spectra of active galactic nuclei (AGN)]. Remarkably, ionized disc reflection and the associated power-law continuum provide a good description of the broad-band spectrum, including the soft excess. There is no requirement for thermal emission from the inner disc in the description of the spectra. The black holes of these systems must then be highly spinning, with a spin close to the maximum rate of a maximal spinning black hole. The results require the action of strong light bending in these sources. We suggest that they could be strongly accreting black holes in which most of the energy is extracted from the flow magnetically andreleased above the disc thereby avoiding the conventional Eddington limit.

Spectral Hardening of Super-Eddington Accretion Flows

Kawashima, Tomohisa[1] ; Ohsuga, Ken[2] ; Mineshige, Shin[3] ; Heinzeller, Dominikus[3] ; Matsumoto, Ryoji[1]

[1]*Department of Physics, Chiba University, Chiba, Japan ;* [2]*National Astronomical Observatory of Japan, Tokyo, Japan ;* [3]*Department of Astronomy, Kyoto University, Kyoto, Japan*

We calculate X-ray spectra of super-Eddington accretion flows with mildly hot outflows by Monte-Carlo techniques, based on two-dimensional radiation hydrodynamic simulation data (Kawashima et al., 2009).

We extend the method of Pozdnyakov et al. (1977) by incorporating radiative processes such as modified blackbody radiation with special relativistic effects (i.e., Doppler shift and aberration) in the photosphere, free-free absorption, photon trapping effects, thermal and bulk Comptonization.

We find that thermal inverse Compton scattering by electrons in the outflow affects the spectral energy distribution (SED) of super-Eddington accretion flows. The fraction of hard emission increases as the mass accretion rate increases. When the isotropic X-ray luminosity is below about 10 times the Eddington luminosity, the SED is similar to the slim disk state. By contrast, when the isotropic X-ray luminosity is larger than about 10 times the Eddington luminosity, the SED becomes harder in the high energy region and deviates from the slim disk state. This result is consistent with the spectral properties of several ultraluminous X-ray sources.

Supercritical Accreiton and ULXs

Mineshige, Shin[1] ; Ohsuga, Ken[2] ; Takeuchi, Shun[1]

[1]*Department o Astronomy, Kyoto University ;* [2]*National Astronomical Observatory of Japan*

We elucidate the theory of supercritical accretion flow onto a black hole and in the context of microquasars and discuss its possible applications to ULXs. We perform global two-dimensional radiation-magnetohydrodynamic (RMHD) simulations of supercritical accretion flow and find the emregence of a RMHD jet, collimated, high-speed outflow which is accelerated by radiation-pressure force and is collimated by the Lorentz force of a magnetic tower formed around the black hole. In addition, the presence of significant uncollimated outflow is the prominent features of the supercritical flow. It will explain the X-ray observations of high luminosity objects indicating the existence of optically thick, low electron temperature plasmas which Compton downscatter soft photons emitted from the underlying optically thick accretion flow.

Chapter 5

Topic 4: Theoretical models for formation and evolution of black holes

The Life and Death of Massive Stars

Fryer, Chris[1]
[1] *Los Alamos National Laboratory*

In the past few decades, we have gradually built up an understanding of the lives of massive stars. But the life and death of the most massive stars remains poorly understood. Here I review what we know and believe about these stars. I will include a review of the diangostics we've identified that will help us better understand their formation and evolution.

Remnants of massive metal-poor stars: viable engines for ULXs

Mapelli, Michela[1] ; Ripamonti, Emanuele[1] ; Zampieri, Luca[2] ; Colpi, Monica[1]
[1] *Dipartimento di Fisica G. Occhialini, University of Milano Bicocca, Milan, Italy ;*
[2] *INAF-Osservatorio astronomico di Padova, Padova, Italy*

Massive metal-poor stars might end their life by directly collapsing into massive (25-80 solar masses) black holes (BHs). We derive the number of massive BHs (N_BH) that are expected to form per galaxy via this mechanism. We select a sample of 64 galaxies with X-ray coverage, measurements of the star formation rate (SFR) and of the metallicity. We find that N_BH correlates with the number of observed ULXs per galaxy (N_ULX) in this sample. We discuss the dependence of our model on the SFR and on the metallicity.

Metallicity estimates in the surroundings of ULXs

Ripamonti, Emanuele[1] ; Mapelli, Michela[1] ; Colpi, Monica[1] ; Zampieri, Luca[2]
[1] *Dip. di Fisica "G. Occhialini", Universita' di Milano-Bicocca, Milano, Italy ;* [2] *INAF - Osservatorio Astronomico di Padova, Padova, Italy*

Massive stellar black holes (25-80 Msun) are ideally suited to power Ultra-Luminous X-Ray sources (ULXs), because they do not require large violations of the Eddington limit.

A likely formation route for such objects involves the direct collapse of massive metal-poor stars. Thus, we test whether there exists a link between low metallicity and the occurrence of ULXs by measuring the metallicity of the HII regions surrounding a few well-studied ULXs.

Models of BH formation- how to make a middle weight black hole

Volonteri, Marta[1]
[1] *University of Michigan*

It is well established that the centers of most galaxies host supermassive black holes with masses of million solar masses and above. These supermassive black holes cannot form from simple stellar evolution of comparable mass stars. They probably evolve from seeds of intermediate mass. In this talk I will address basic, but critical, questions on the cosmological significance of massive black holes. What physical mechanisms lead to the formation of the first massive black holes? How massive were the initial massive black hole seeds? When and where did they form? I will mostly focus on astrophysical processes that happen in the first galaxies, and I will consider three possibilities: that massive black holes are the remnants of the first generation of stars, that massive black hole formation is triggered by gas-dynamical instabilities, that massive black hole seeds are formed via stellar-dynamical processes. I will also discuss possible observational tests that can be performed with current and future instruments to discriminate among different scenarios

The Black Hole in NGC 1313 X-2

Zampieri, Luca[1] ; Patruno, Alessandro[2]
[1] *INAF-Astronomical Observatory of Padova ;* [2] *Astronomical Institute "A. Pannekoek", University of Amsterdam*

The research activity on ULXs has grown much in the last couple of years, leading to some important discoveries and advancements, such as the tentative identification of an orbital modulation (about 6 days) from the optical counterpart of NGC1313 X-2. Several studies have been carried out on this source. The amount of data available make it a cornerstone for the study of ULXs. We re-analyzed the optical and X-ray data of NGC1313 X-2 with homogeneous criteria and modelled them with a binary evolution code that takes into account for X-ray irradiation. We restricted the candidate binary system to be either a 50-100Msun black hole accreting from a 12-15Msun main sequence star or a 20Msun black hole with a 12-15Msun giant donor. If the orbital period of the system is 6 days, a 20Msun black hole model becomes unlikely and we are left with the only possibility that the compact accretor in NGC1313 X-2 is a massive black hole of 50-100Msun. We will discuss these results within the framework of an alternative scenario for the formation of ULXs, in which a portion of them may contain BHs of 30-90 solar masses formed from very massive stars in a low metallicity environment.

Chapter 6

Topic 5: Hot topics

X-ray populations in galaxies

Gilfanov, Marat[1]
[1] *MPA, Garching, Germany*

I will summarize current status of our understanding of populations of accreting X-ray sources in galaxies. Their luminosity distributions in late and early type galaxies observed by Chandra and XMM-Newton are well described by respective "universal" luminosity functions. There is a qualitative difference between LFs of X-ray sources in young and old galaxies, reflecting the difference in accretion regimes in high- and low-mass X-ray binaries. Although relatively bright sources, log(Lx)>39, are observed in galaxies of all morphological types, the truly ultra-luminous sources with log(Lx)∼40 are associated with regions of intense star formation. The numbers of high-mass X-ray binaries observed in star-forming galaxies indicate the rather high probability for a massive star to become an accretion powered X-ray source once upon its lifetime. This explains the unexpectedly high contribution of accreting neutron stars and stellar mass black holes to the Cosmic X-ray background, ∼! 7-10%. I will also present the evidence that luminous X-ray sources may be formed in significant numbers near galactic centers via tidal captures of low mass stars by stellar mass black holes.

Multiwavelength studes of ULXs: Clusters, Bubbles and Optical Counterpart

Pakull, Manfred [1]
[1] *Observatoire Astronomique, Strasbourg, France*

The question of whether ULXs harbour stellar mass black holes or rather a new class of intermediate mass black holes has not yet been answered. X-ray observations alone cannot resolve the issue, and information from other wavelengths are crucial. Here I will summarize results from recent optical and radio observations. Optical observations with 8m telescopes have revealed parent stellar clusters, and several faint blue counterparts display broad HeII4686 emission, a hallmark of X-ray heated accretion disks. However, a definite mass determination of the binary components has not yet been achieved.

Possibly even more revealing properties of ULXs come from the presence of huge shock-ionised surrounding bubbles. ULX bubble energetics suggest mechanical powers that are of the same order of the 10^{39} - 10^{40} erg/s X-ray luminosities. I will discuss our recent discovery of the SS433/W50-like microquasar S26 in the galaxy NGC 7793. It consists of a faint, central hard X-ray source, a 300 pc diameter optical/radio bubble and pronounced X-ray/radio hot spots akin to FRII radio galaxies. S26 appears to be a rosetta stone for our understanding of the relation between ULXs and microquasars and of the accretion processes of black holes and their feedback onto the interstellar medium.

Dynamical constraints on the mass of the black hole in a ULX

Roberts, Timothy[1] ; Gladstone, Jeanette[2] ; Swinbank, Mark[1] ; Goad, Michael[3] ; Levan, Andrew[4] ; Ward, Martin[1]

[1]*Department of Physics, Durham University, Durham, UK ;* [2]*Department of Physics, University of Alberta, Edmonton, Canada ;* [3]*Department of Physics & Astronomy, University of Leicester, Leicester, UK ;* [4]*Department of Physics, University of Warwick, Coventry, UK*

We present the results of a Gemini campaign to constrain the mass of the black hole in an ultraluminous X-ray source via optical spectroscopy. We do this by searching for radial velocity variations in the He II 4686 Angstrom line. If present, they suggest that this line is likely to be dominated by reprocessed X-rays from the outer accretion disc, and the variations can be used to constrain the motion of the black hole around its companion star. Pilot studies of the optical counterparts of a number of ULXs revealed two strong candidates for further detailed study. Our campaign found that one of these two ULXs shows no radial velocity variations; however the other appears to show significant, potentially periodic shifts in its He II line emission over timescales of days. We will discuss the implications of this data for the mass of the black hole in this system.

Name Index