Relativity from Chandra to Constellation-X

MG11 - Saturday, July 29, 2006

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  SAO Con-X Science Lead
• Words from DETF – ‘It is not at present possible...to determine whether $\Lambda$, a dynamical fluid, or a modification to GR is correct explanation of the observed accelerating Universe ... any observational evidence for modifications of GR... may point the way toward understanding DE...[and have] far reaching implications for other fields of physics.’

• Gravity as described by GR has yet to be tested in the Strong Field limit

• Observations of Black Holes = Strong Field Gravity

• Will Review Key Chandra Results and Way Forward with Constellation-X
IAUS 230 Dublin ‘Gravity Bar’
CHANDRA has brought X-ray Imaging to <1”
Comparable with typical optical/IR telescopes
But most X-ray SPECTRA are still ‘colors’
typically $N_H$, $K_t$, equivalent of U/B/V – Except for the brightest sources with gratings, or VERY long exposures

Constellation-X will change this – Routine spectra with $300 < R < 3000$ for tens of thousands of sources – $F_X \sim 10^{-15}$ ergs/cm$^2$/s (0.25-2keV)
100 times throughput for $R>300$, AREA alone 40x Chandra, 20x XMM at Fe-K (strongest emission line)
The PHYSICS is in the Spectra!
Example:
Chandra has resolved the X-ray background into active galactic nuclei (AGN) with a space density of a few thousand per sq deg

• Constellation-X will gather high-resolution X-ray spectra of the elusive optically faint black hole X-ray sources

• Chandra deep surveys have the sensitivity to detect AGN up to z~8

2 Megasecond Observation of the CDF-N (Alexander et al. 2003)

Chandra sources identified with mix of active galaxies and normal galaxies, many are optically faint and unidentified.
• Large fraction of the background identified with moderate-redshift (1 < z < 3) AGN (e.g., Barger et al. 2003)
• Constellation-X will provide detailed spectroscopic IDs
• 100ks at 2 x 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}

Con-X simulations of faint z=1.06 “Type II QSO”
Chandra has detected X-ray emission from three high redshift quasars at \( z \sim 6 \) found in the Sloan Digital Sky survey.

Flux of \( 2-10 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) beyond grasp of XMM-Newton, Chandra or Astro-E2 high resolution spectrometers, but within the capabilities of Constellation-X to obtain high quality spectra.

High resolution spectroscopy enables study of the evolution of black holes with redshift and probe the intergalactic medium of the early universe.
The high redshift universe of AGN

Constellation-X will gather high quality spectra of these faintest X-rays sources that make up the X-ray background, like this $z = 3.7$ type II quasar discovered serendipitously by Chandra.
Black Holes – From Astrophysics to Physics

- **Stage I – Identify BH Candidates**
  - ASM -> Chandra Pos/Spectra -> optical f(m)
  - Resolve Cosmic X-ray Background

- **Stage II – Confirm BH Candidates**
  - Event Horizons (Chandra), Timing, Spectra
  - $L / L_{\text{Bondi}}$ Radiatively inefficient flows

- **Stage III – Measure Spin of BH**
  - Spectra, Timing (Chandra, XMM, RXTE -> Con-X)

- **Stage IV – Relate Spin to Penrose, BZ**
  - Jets, Chandra, VLA, Con-X

- **Stage V – Quantitative tests of Kerr Metric**
  - Doppler Tomography, Reverb Mapping, $T < T_{\text{ORB}}$ Con-X

J McClintock
Chandra: Confirming Black Hole Candidates

Soft X-ray Novae in Quiescence

\[ \log(L_x / L_{Edd}) \]

- Neutron stars
- Black Holes

**Quiescence**
- Neutron Stars
- Black Holes

Narayan et al. 1997
Garcia et al. 2001

M. Garcia, MG11
Bondi Accretion Rates in Nearby SMBH

- When $R_{\text{Bondi}}$ resolved, accretion rate known

Chandra resolves in several nearby galaxies

Accretion must be radiatively inefficient – ADAF, CDAF, RIAF – all with event horizon

SgrA – Baganoff et al
M31 – Garcia et al
The Iron fluorescence emission line is created when X-rays scatter and are absorbed in dense matter, close to the event horizon of the black hole.

Theoretical ‘image’ of an accretion disk.
RELATAVISTIC Fe Lines in Stellar and SMBH

J. Miller MG10

- Prior to 1999
  - GX 339-4
  - Cygnus X-1
  - V404 Cyg ??

- After 1999
  - GS 1354-645
  - 4U 1543-475
  - XTE J1550-564
  - XTE J1650-500
  - GRO J1655-40
  - GX 339-4
  - SAX J1711.6-3808
  - XTE J1720-318
  - XTE J1748-288
  - V4641 Sgr
  - XTE J1859+226
  - XTE J1908+094
  - GRS 1915+105
  - Cygnus X-1
  - XTE J2012+381

Streblyanskaya et al 2004
XMM Lockman Hole 0.8Ms

Average rest-frame spectra show relativistic Fe-lines

Type-1 AGN
EW~700

Type-2 AGN
EW~500
Spin via Fe Line Profile in BH Binaries

GX 339-4 (CXO)

GRS 1915+105 (CXO)

GX 339-4 (XMM)

a > 0.9-0.8

XTE J1650-500 (XMM)

a ~ 1, BZ?
• Spin Changes the Geometry of BH

Radius
ISCO
Binding
Energy
Frequency

J. McClintock

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Constellation-X: Reverberation Mapping
Probes Stage III, IV, and V

Courtesy Chris Reynolds (UMD)

Strong Field GR tests. ‘Snapshot’ of Geometry - Derive: Mass, Spin, Geometry – $F_\times \sim 5 \times 10^{-11}$ ergs/cm$^2$/s(2-10)
GR well tested in weak field – but not all of applicable parameter space. Technique used in OPTICAL at many $R_S$ to estimate black hole mass
Con-X: Reverberation Mapping Sets Minimum Area

\[ a=0, \ M=10^7, \ A=0.6m^2 \]

\[ a=1, \ M=10^7, \ A=0.6m^2 \]
Con-X: Spin via Doppler Tomography

• Orbital Time scale 10x Reverb Mapping: $F_X \sim 5 \times 10^{-12}$ ergs/cm$^2$/s(2-10)
• Follow dynamics of individual blobs in disk
• **Quantitative** test of orbital dynamics in strong field regime (STAGE V)

Strong Field domain largely untested – most test utilize FFTs, time averaged line profiles.

Stage IV: Spin, Jet, AGN, Galaxy Coupling

- Black Holes clearly effect their environment: Feedback (jets, B-Z effect), M-σ – what are BH properties vs z?
Black Holes (AGN) peak at $z \sim 1.5$, common $0 < z < 4$

- Time averaged Fe profiles, calibrated by time-resolved, will allow:
  - Investigate evolution of black hole properties (spin and mass) over a wide range of luminosity ($F_x 10^{-11} - 10^{-14}$) and redshift ($0 < z < 4$)
  - Use Line profile to determine black hole spin ($a$ to $10\%$)
We expect true $f_{\text{gas}}(z) = M_B/M_T$ values to be approximately constant with redshift. However, measured $f_{\text{gas}}(z)$ values depend upon assumed distances to clusters $f_{\text{gas}} \propto d^{1.5}$. This introduces apparent systematic variations in $f_{\text{gas}}(z)$ depending on the differences between the reference cosmology and the true cosmology.

**SCDM ($\Omega_m=1.0, \Omega_=0.0$)**

**\_CDM ($\Omega_m=0.3, \Omega_=0.7$)**

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**Inspection clearly favours _CDM over SCDM cosmology.**

*Steve Allen et al*
Clusters CAN be used as ‘standard’ candles – kT, Fx, size -> Distance, 26 Chandra clusters Allen etal 2004 MNRAS

SNIa distance systematics at ~7% (statistical = 13%, Riess etal 2004 gold sample 157 SN, z<1.8) Chandra clusters show NO systematics (yet) at 10% (or 5% gold) level.

A large Con-X snapshot survey followed by deeper spectroscopic observations of relaxed clusters will achieve \( f_{\text{gas}} \) measurements to better than 5% for individual clusters:

- Corresponds to
  \[ \Omega_M = 0.300 \pm 0.007, \Omega_\Lambda = 0.700 \pm 0.047 \]
- For flat evolving DE model,
  \[ w_0 = -1.00 \pm 0.15, w' = 0.00 \pm 0.27 \]
• Vikhlinin et al. 2006
• T correlates with \( f_{\text{gas}} \)
• Different set of clusters…
• Trend not obvious for \( T > 5 \text{keV} \)

• Allen et al. 2006 in prep
• NO correlation of \( T \) with \( f_{\text{gas}} \)
• Best fitting power-law model is consistent with a constant at 1\( \sigma \)
• **Must select hot (>5keV), luminous(>10^{45}) clusters**

Must select against systematics – ConX with \( R = 1500 \) at 6keV, can do this by detecting non-virial motions (mergers, shocks), accurate \( T \), mass measurements.
The sources are luminous and relatively bright X-ray sources, easily found in wide field surveys (20-40 per sq deg at Con-X flux limits).

Provides precise Cosmological parameters, e.g. contours in the $\Omega_m$ and $\sigma_8$ space from Allen et al (2003):

- ROSAT+Chandra $z<0.5$ luminosity function (blue)
- Galaxy counts plus WMAP1 (black)
- WMAP1 alone (yellow orange)

The $\sim 0.75$ value of $\sigma_8$ recently confirmed with WMAP3.
Chandra: The Puzzling Case of RX J1856.5-3754

Burwitz et al. 2003
The physical constituents of neutron star interiors remain a mystery. Constellation-X will finally provide the answers by determining the equation of state using multiple techniques: spectra and timing.

10 eV EW absorption lines can be detected with Con-X in single bursts.
Pulse shapes of burst oscillations encode information on the neutron star mass and radius.
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.

Statistical limits from Constellation-X for even just a single burst will provide meaningful constraints on EOS.

Strohmayer (2003)


Con-X can be Gracefully (re)-Scaled

- Con-X ‘Lite’
- 3 Telescopes meet Area Requirements
- Grating Spectrometer -> Low-E/Hybrid Calorimeter, Innovative Grating?
- Hard X-ray Telescopes -> Multilayers?
- 100 kg, $0.1B for science enhancement
- Savings of $0.5B

Savings of $0.5B vs 4 + 12 Tele + Gratins single s/c version

Minimum possible mission
Chandra has brought X-ray imaging on par with that at optical wavelengths. Constellation-X will do the same for X-ray spectroscopy.

X-ray Background:
- Chandra Resolves, ~2/3 unknown
- Con-X will give X-ray IDs, z, spin, BZ
- Stage III, IV, V

Dark Energy/Matter:
- Chandra measures $\Omega_M$,$\Omega_\Lambda$
- Con-X will measure w, w'

Coeval growth of BH and Galaxies:
- Chandra explains Cooling Flows
- Con-X will measure outflows, spin, mass, abundance, vs z, cosmic feedback?
- Stage III, IV, V
• Backup/extra slides follow
Constellation-X

20-100 times increased sensitivity for spectroscopy

Chandra
XMM-Newton
Astro-E2

0.1-0.35 m²
0.5-90 arc sec

Constellation-X endorsed by NAS McKee-Taylor Survey & Q2C report as high priority mission for this decade

First Clusters of Galaxies

3 m²
5-15 arc sec

Maxim
10 Million times finer imaging

0.1-1.0 m²
0.1 micro arc sec

Generation-X
1000 times deeper X-ray imaging

50-150 m²
0.1-1 arc sec

First Black Holes & Galaxies

Black Hole Event horizon
F_{gas} from First Principles

Assume: Hydrostatic Equilibrium (must select virialized, relaxed clusters)
Radiating (=baryonic)/Dark Matter constant and representative
Then: Can measure relative D (~DE) and knowing f_{gas}, absolute D (~DM)
because x-ray measurements of f_{gas} \sim D^{3/2}

\[ \text{Measure } T, F_X, \phi \]
\[ \text{Compute } R, M_T, M_B \]

\[ \frac{GM_T}{R} = \kappa T \]
\[ F_X = \text{const } T^{1/2} n_e^2 R \]
\[ n_e (\sim n_B) = F_X / (\text{const } T^{1/2} D \sin \phi))^{1/2} \]
\[ n_e \sim D^{-1/2} \]

\[ f(\text{gas}) \sim M_B / M_T \sim D^{3/2} \]

hydro equilb – includes Dark Matter
Bremsstrahlung Equation
non-X-ray baryons fixed \sim 1/6 n_B

\[ M_T = 1/2 \frac{kTR}{G} \sim D \]
\[ M_B = 4/3 \pi n_e R^3 \sim D^{1/2} D^3 \]
\[ M_B \sim D^{5/2} \]

measure f_{gas} vs z(d)
IF f_{gas} not constant – z(d) diff
diff z(d) = Dark Energy

Abs[f_{gas}] = Dark Matter