Con-X Science Booklet: Released Summer 2005

Science with Constellation-X

Studying Dark Energy, Black Holes and Cosmic Feedback at X-ray Wavelengths: NASA's Constellation-X Mission

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http://constellation.gsfc.nasa.gov
Outline

• Constellation-X Mission
• Dark Energy Constraints using Galaxy Clusters
• Black Holes & Strong Gravity
• Cosmic Feedback in the X-ray Band
The Beyond Einstein Program

Science and Technology Precursors

- WMAP
  - microwave background detection
- LIGO
  - gravitational wave detectors
- Hubble
  - optical imaging
- Chandra
  - x-ray imaging
- GLAST
  - mega-channel electronics

INFLATION PROBE
- LISA
- space interferometry, gravitational wave detection

BIG BANG OBSERVER
- big bang physics

DARK ENERGY PROBE
- LISA
- space interferometry
- dark energy physics

BLACK HOLE IMAGER
- black hole physics

CONJUNCTION-X
- mega-channel electronics

GREAT OBSERVATORIES

BLACK HOLE FINDER PROBE
- black hole census

PROBES
- dark matter physics

VISIONS
The Constellation-X Mission

- Black Holes:
- Dark Matter and Dark Energy
- Cosmic Feedback
- Life Cycles of Matter and Energy

Observatory dedicated to high resolution X-ray spectroscopy:
- 25-100 times sensitivity gain over Chandra
- Baseline of four space-craft working as a single large telescope

Constellation-X given strong endorsement by US National Academy of Sciences McKee-Taylor & Turner Committee Reports

Ann Hornschemeier, Science with Constellation-X
X-ray Mission Collecting Areas

![Graph showing effective area vs energy for different missions including Constellation-X, Suzaku, XMM RGS, ASTRO-E2 XRS, Chandra, and LETG](image)

**Effective Area (cm²)**

*Energy (keV)*

**Constellation-X (R>300)**

**Suzaku**

**ASTRO-E2 XRS**

**XMM RGS**

**Chandra**

**LETG**

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Resolving Power: Collecting Area vs. Spectral Resolution

Gratings: fixed $\Delta \lambda$

Calorimeter: fixed $\Delta E$

Effective Area ($\text{cm}^2$) vs. Spectral Resolution ($R=E/\Delta E$, FWHM) graph

- Con-X RGS
- Con-X XMS
- Suzaku XRS
- Chandra HETG (MEG)
- XMM RGS
High Spectral Resolution in the X-ray Band
Notes on X-ray Spectroscopy

- X-ray spectroscopic workhorse: the He-like triplet \( \rightarrow \) density and temperature diagnostics
- This guides our spectral resolution requirements for hot X-ray plasmas:
  - Thermal broadening limits resolution to \( R \approx 410 \sqrt{M/T} \)
  - Practical maximum for X-ray plasmas is \( R \approx 10,000 \)

Procyon XMM RGS spectrum (Ness et al. 2001)
Notes on X-ray Spectroscopy

- Absorption spectra of cool plasmas, however, contain complex velocity structures
- Example: NGC 3783, nearby Seyfert 1 (900 ks Chandra HETG; Kaspi et al. 2002)
  - RED: H-like lines
  - BLUE: He-like lines
  - GREEN: Other ions, e.g., lower ionization-metals Fe XVII and Fe XXIV
- Constellation-X, with its large effective area, will collect a spectrum of similar quality in 50-100 ks
Constellation-X
Science
Con-X Science

**Black Holes**
- What is the detailed structure of the inner accretion disk?
- How prevalent are intermediate-mass black holes?
- Does dark energy evolve with redshift?

**Dark Energy & Matter**

**Cosmic Feedback**
- How have accretion disks in AGN affected galaxy evolution?
- How do starburst galaxies enrich the IGM?
- What is the nature of matter that makes neutron stars?
- How do stellar outflows affect planet formation?

**Life Cycles of Matter**
Galaxy Clusters: Constraints on Dark Energy
(thanks to Steve Allen, Stanford)
Cosmology with galaxy clusters

1. Galaxy clusters, like supernovae, have a measured property that can be used for distance-$z$ comparisons ($f_{\text{gas}}$ measurements; e.g., Allen et al. 2002, 2004)

2. Also, number density, spatial clustering and evolution of clusters are all strong functions of dark energy (Cluster luminosity/mass function measurements; e.g., Majumdar & Mohr 2003)

Both require large samples (>> hundreds) of large, dynamically relaxed clusters where hydrostatic equilibrium holds (identified in e.g., the ROSAT All Sky Survey)
X-ray Emission from Clusters of Galaxies

- X-ray emitting gas dominates the overall baryonic mass in clusters ($M_{\text{gas}} \approx 6M_{\text{stars}}$; e.g., Fukugita, Hogan & Peebles 1998).

- Observables:
  1. X-ray surface brightness profile.
  2. Deprojected (spectrally-determined) temperature ($kT$) profile
     + assumption of hydrostatic equilibrium

Chandra image of MACS1423+24 (z=0.54)
$f_{\text{gas}}$ Measurements with Clusters of Galaxies

- Galaxy clusters are so large that their matter content should provide a fair sample of matter content of Universe.

If we define:

$$f_{\text{gas}} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}}$$

Then:

$$f_{\text{baryon}} = f_{\text{gal}} + f_{\text{gas}} = f_{\text{gas}}(1 + 0.19h^{0.5})$$

Since clusters provide ~ fair sample of Universe

$$f_{\text{baryon}} = b_{\text{b}}/b_{\text{m}}$$

$$\Omega_{\text{m}} = \frac{b\Omega_{\text{b}}}{f_{\text{baryon}}} = \frac{b\Omega_{\text{b}}}{f_{\text{gas}}(1+0.19h^{0.5})}$$

Ann Hornschemeier, Science with Constellation-X
$f_{\text{gas}}$ Dependence on Distance

- The measured $f_{\text{gas}}$ values depend on the distance to the clusters as $f_{\text{gas}} \propto d_A^{1.5}$
- Distance dependence arises from geometry and assumption of hydrostatic equilibrium

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

CDM ($\Omega_m=0.3$, $\Omega_\Lambda=0.7$)
Cosmological Parameters
(Allen et al. 2005 DETF Paper)

- Con-X’s effective area critical to study large sample of clusters
- Expect a large 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 $\Omega_{M}=0.300\pm0.007$, $\Omega_{\Lambda}=0.700\pm0.047$
  - For flat evolving DE model, $w_{0}=-1.00\pm0.15$, $w' = 0.00\pm0.27$

Constraints are similar & complementary to SN Ia studies
Black Holes: Strong Gravity and the Inner Accretion Disk
Fe Kα: Accretion Disk Structure

- Fe K fluorescence from surface layers of thin, Keplerian accretion disk
- Chandra/XMM beginning to probe structure on orbital/sub-orbital timescales in outskirts of accretion disk
- Con-X will do the same for ~100-200 nearby AGN

Credit: Turner et al. (2005; astro-ph/0506223)
Beyond Einstein: 
*Probing Strong Gravity with Constellation-X*

- 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.

- Test of General Relativity in the strong field regime

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**ASCA X-ray spectrum of MCG-6-30-15**

**Tanaka et al. 1995**

Theoretical ‘image’ of an accretion disk.
Inner Accretion Disks: MCG-6-30-15

- MCG-6-30-15 (d=37 Mpc)
- $M_{\text{BH}} \sim 10^6 \text{ – } 2 \times 10^7 M_\infty$
- Strong time variability of line profile: emission at <6 gravitational radii
- Relatively common in ASCA studies of Seyferts (14/18 have resolved Fe K lines; Nandra et al. 1997)
- Typically line energy $\sim 6.4$ keV and $\sigma=0.43\pm 0.12$ keV

ASCA X-ray spectrum of MCG-6-30-15
Tanaka et al. 1995
Constellation-X’s Role: Reverberation Mapping

- Current limitation: vast range of black hole angular momentum fits same Fe K data (e.g., Dovciak, Karas & Yaqoob 2004)
- Con-X will track X-ray flares across accretion disks via reverberation effects, constraining the nature of space-time around black holes (Young & Reynolds 2000)
Tracking material around accretion disks with X-ray spectroscopy allows us to probe the nature of space-time very near the black hole.
Cosmic Feedback
Definition of Feedback

• Definition of feedback:
  – *Return, via outflows, of mechanical energy, radiation, and chemical elements from star formation and black holes to the interstellar and intergalactic medium*
  – Self-regulation of processes across vast scales (e.g., correlation between stellar bulge mass, velocity dispersion and nuclear black hole mass in galaxies: Magorrian relation)
AGN Feedback

• Large scale-structure simulations require AGN feedback to regulate the growth of massive galaxies (e.g., Di Matteo et al. 2005, Croton et al. 2005)
• Non-dispersive X-ray spectroscopy of clusters needed to probe hot plasma (Begelman et al. 2003, 2005)
• Powerful AGN outflows in the Universe at $z=1-3$ ⋆
  Chandra/XMM have studied highly ionized outflows in local AGN (NGC 3783; Kaspi et al. 2002)

Con-X simulation of BAL QSO (S.Gallagher, UCLA)

Perseus Cluster of Galaxies (Chandra image)
Supernova (Stellar) feedback
Wind plasma diagnostics (D. Strickland, JHU)

M82 Chandra central 5x5 kpc
0.3-1.1 keV,
1.1-2.8 keV
2.8-9.0 keV

Simulated 20 ks Con-X
northern halo observation,
0.3-2.0 keV.

O VII and O VIII region.
Well resolved triplet,
high S/N in continuum.

With calorimeter ~2-eV resolution we can determine
\( T, n_e, t, [Z/H], v_{\text{HOT}} \) accurately in many extended winds (not just M82).
Hot gas around normal disk galaxies

courtesy of D. Strickland (JHU)

Normal spiral galaxies

Example starburst galaxy with superwind

NGC 4013  NGC 4217  NGC 891  NGC 3628

Red: H-alpha (WIM), Green: R-band (starlight), Blue: Diffuse soft X-ray (3 million deg gas).
The region covered by each image is 20 x 20 kpc. Intensity scale in square-root.
Interested in more Constellation-X Science?
Available in PDF form at constelltion.gsfc.nasa.gov
THANK YOU

- Please visit
  http://constellation.gsfc.nasa.gov

- **Questions? Email me:**
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**Constellation-X**

**Facility Science Team**

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