X-ray observations of neutron stars and black holes in nearby galaxies

Andreas Zezas

Harvard-Smithsonian Center for Astrophysics
The lives of stars: fighting against gravity

- **Defining parameter:** Mass

- To avoid implosion, stars must generate energy from fusion reactions.

- The stages of stars are determined by the type of fuel left: hydrogen, helium, carbon etc.
...but, after some time they run out of fuel

White dwarf ($\lesssim 8 \, M_\odot$)

Supernova ($\gtrsim 8 \, M_\odot$)

Neutron star ($M \sim 1.4-3.0 \, M_\odot$)

Black-hole ($M > 3.0 \, M_\odot$)
Black-holes and Neutron stars

- **Neutron stars (≈1.4M☉):**
  - Pulsars (magnetized NS)
  - Non-magnetized NS

- **“Stellar” Black-holes (1.4 - ~20M☉)**

- **“Supermassive” Black-holes (>10⁶ M☉)**

Some numbers:

<table>
<thead>
<tr>
<th></th>
<th>Mass (M)</th>
<th>Radius (km)</th>
<th>Temp. (K)</th>
<th>Density (ton/cm³)</th>
<th>Rotation (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Dwarves</td>
<td>&lt;1.4</td>
<td>5x10³</td>
<td>10⁴-10⁵</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Neutron stars</td>
<td>1.4-3</td>
<td>10-20</td>
<td>~10⁷</td>
<td>2x10⁸</td>
<td>10⁻³-10³</td>
</tr>
<tr>
<td>Black holes</td>
<td>&gt;3</td>
<td>&gt;10</td>
<td>10⁵-10⁷</td>
<td>inf</td>
<td>?</td>
</tr>
<tr>
<td>Sun</td>
<td>1</td>
<td>7x10³</td>
<td>5700</td>
<td>1.4x10⁻⁶</td>
<td>27 days</td>
</tr>
</tbody>
</table>
How do we find them

• **Accretion**!
  - binary stars (X-ray binaries)
  - interstellar gas (supermassive BH)

When gas falls onto a BH/NS it forms a rotating accretion disk, like water swirling down the drain.
How do we find them

- **Accretion disks**: Gravitational energy of gas is converted to thermal energy

  \[ L = \frac{GM mc^2}{R} \]

  For BH, NS \( GM/R \sim 0.1 \)

  For \( M=10 \, M_\odot \), \( L = 2 \times 10^{32} \, W = 10^7 \, L_\odot \)

  \( M=1 \, M_\odot \), \( L = 2 \times 10^{31} \, W = 10^6 \, L_\odot \)
The complicated lives of binary stars
Studying X-ray binaries

• Why bother?
  • Stellar evolution
  • General relativity (extreme gravity)
  • Extreme physics (very hot, dense matter)
  • Is exciting!

• How?
  • Find them (detection)
  • Spectroscopy
  • Timing (light curves, power spectra etc)
  • Spatial distribution
Detection

• Problems
  - Background
  - Confusion
Detection

- Problems
  - Background
  - Confusion
  - Point Spread Function
  - Limited sensitivity

CDF-N

Brandt et al, 2003
Detection

70 Ksec

411 Ksec
• Methods
  • Sliding cell
  • Wavelets
  • “Divide and conquer”
Detection

• Statistical issues
  • Source significance: what is the probability that my source is a background fluctuation?
  • Intensity uncertainty: what is the real intensity (and its uncertainty) of my source given the background and instrumental effects?
  • Extent: is my source extended?
  • Position uncertainty: what is the probability that my source is the same as another source detected 3 pixels away in a different exposure?
  • Completeness (and other biases): what is the probability that my source is associated with sources seen in different bands (e.g. optical, radio)?
• Completeness (and other biases): How many sources are missing from my set?
Spectra

• **Spectra**: Intensity as function of energy

• **Standard method**: Fit spectra with models describing physical processes
  
e.g. Disk-BB to measure BH mass

\[
T \approx 2 \times 10^7 \left( \frac{M}{M_*} \right)^{-1/4} \text{ K}
\]

power-laws to distinguish pulsar from BH binaries

\[
I_E = K \times e^{-N \sigma(E)E^{-\Gamma}}
\]

Miller et al, 2004
Statistical issues:

- Significance of components
- Correlated parameter uncertainties
- Estimation of source intensity

\[
I \approx \int_{E_{\text{low}}}^{E_{\text{up}}} I(\text{params}, E) dE
\]

where params (e.g. T, \(N_H\), photon index) often have correlated uncertainties

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Spectra: bright sources

Zezas et al, 2002
Spectra: few counts

- Few counts: Use hardness ratio
  Ratio (in various flavors) of intensity in two bands, e.g.:

\[ R = \frac{H}{S}, \quad R = \frac{S - H}{S + H}, \quad C = \log\left(\frac{H}{S}\right) \]

- Problems:
  - HRs in the Poisson regime (T. Park)
  - Separate source populations in HR diagrams (mixing etc)

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\[ \text{Zezas et al, 2002} \]

\[ \text{Prestwich et al, 2003} \]
• Accreting sources are variable
  Now we can do this in other galaxies!

• Looking for:
  • Variable sources (flickering, systematic trends) → Identify binaries
  • Pulsations → Identify pulsar binaries
  • Variability amplitude
  • Spectral variability → Determine binary types; study the accretion process
Variability

- **Methods**
  - $\chi^2$, KS test
  - rms excess variance
  - Fourier analysis (power-spectra)
  - Bayesian blocks

- **Problems:**
  - FAINT sources
  - uneven sampling

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Markowitz et al 2003

Fairall 9

NGC 3783

Temporal Freq. (Hz)
Spatial distribution

• Questions:
  • Separate point-like from extended sources
  • Study spatial distribution of sources
    Comparison with optical/radio etc
    Significance of spatial patterns (or, is it really spiral?)
  • Comparison between different populations
    (e.g. BH, neutron stars, SSS)
Spatial distribution

Goals:

• Separate point-like from extended sources
Spatial distribution
Luminosity functions

• Definition

\[
\frac{dN}{dL} = K' \times L^{-(\alpha+1)}
\]

or

\[N(>L) = K \times L^{-\alpha}\]

• Why is important?
  • Provides overall picture of source pops
  • Compare with models for binary evolution

Kong et al, 2003
Luminosity functions

- **Statistical issues**
  - Incompleteness
    - Background
    - PSF
    - Confusion
  - Other biases
  - Non parametric comparison taking into account all sources of uncertainty
Fornax-A

$\alpha_{\text{cum}} = 1.3$

$\text{L}_x = 10^{38}$ $4 \times 10^{38}$

Kim & Fabbiano, 2003
Luminosity functions

$N (> L_X)$

$log(L_X) (0.1-10.0 \text{ keV})$
Luminosity functions

- **Statistical issues**
  - Incompleteness
  - Other biases
  - Non parametric comparison taking into account all sources of uncertainty
  - Spectrum dependent incompleteness
Summary

• Accreting binary systems are very interesting objects which allow us to study aspects of fundamental physics and astrophysics.
• For these studies we use techniques involving spectral, timing and spatial data.
• With the new generation of X-ray satellites, we can study black-holes and neutron stars in environments other than our galaxy.
• However, we still need powerful statistical tools in order to apply these techniques on our data.