X-ray Emission from Compact Objects

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Lecture 2
Introduction

- How X-ray data are used to determine fundamental physical parameters of compact objects (NS and BH)
- How these parameters change with time
- What these measurements tell us about the physics under extreme conditions of temperature, density, magnetic field and strong gravity
- Interesting gravitational effects not observable in the laboratory
Agenda

- Physical Parameters of X-ray Binaries:
  - spin — magnetic field
  - radius — orbital elements
  - mass

- Relativistic Effects
  - evidence for event horizon in BH
  - evidence for BH spin
  - Lense-Thirring effect ("frame-dragging")
  - jet formation in BH systems
  - gravity wave generation from rotating NS
Vocabulary

- Equation of state: \( P = P(\rho) \) – determines the relationship between the M and R for compact objects. In a “soft” EOS, the average system energy is attractive at \( \rho_{\text{nuc}} \approx 2.8 \times 10^{14} \ \text{g cm}^{-3} \), while for “stiff” EOS, energy from repulsive interactions dominates at \( \rho > \rho_{\text{nuc}} \). This extra pressure against gravitational collapse produces NS with higher maximum M, larger R for a given M, thicker crusts and lower central densities.

- Lense-Thirring effect (aka frame-dragging): A prediction of GR. A torque-free gyroscope will precess relative to an inertial frame at infinity. For XRBs, particles in accretion disks tilted with respect to the spin axis may precess as they orbit the rotating NS or BH.
Vocabulary

- **Prograde system**: one in which the accreting material has the same angular momentum direction as the spin of the compact object. The object should spin up (faster) as $f(t)$.

- **Retrograde system**: one in which the accreting material has the opposite angular momentum direction as the spin of the compact object. The object should spin down (slower) as $f(t)$.

- **X-ray nova**: transient intense emission which lasts for ~months out of ~years.
Physical Parameters

- Spin - directly observable in NS pulsars

![Graph](image.png)

**4U0115+63 - SAS-3 data**

- 3.6 s

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Cominsky et al. 1978
Spin Evolution

- Accretion torque model - pulsars should spin up as angular momentum is transferred from accreting material.

Predicted curves from Ghosh and Lamb (1979) for different values of the magnetic moment $\mu$ in units of $10^{30} \text{ G cm}^3$.
Spin Histories

- BATSE: continuous P monitoring shows that NS spend ~equal times spinning up and down and that spins reverse on timescales of ~days! Retrograde accretion disks?

disk fed

Be disk

wind fed

wind fed

4000 days

5000 days
Magnetic Field

- Cyclotron line absorption in X-ray pulsars - phase averaged data from Ginga

\[ E = \frac{\varepsilon h B}{2\pi m_e} \]

\[ B \sim 0.86 \times 10^{12} \, G \]

\[ *(E/10\text{keV}) \]

Note that:

\[ E_{\text{obs}} = \frac{E}{1+z} \]

where \( 1+z \) is the redshift:

\[ 1+z = (1-2GM/Rc^2)^{-1/2} \]

\[ z \sim 0.3 \, \text{(typical)} \]
Magnetars

- Soft Gamma Repeaters are Magnetars!

25 years

- SGR 1806-20 in SNR
- SGR 0526-66
- SGR 1900+14
Magnetars

- Associated with young supernova remnants
- Repeated bursts of low energy gamma-rays
- Burst peak luminosity is $10^{41} \text{ erg s}^{-1} \sim 10^3 \times L_{\text{edd}}$

For SGR 1806-20, $P=7.47$ s

$\dot{P} = 2.6 \times 10^{-3} \text{ s y}^{-1}$ which yields

$B = 2 \times 10^{14} \text{ G}$ and

$\tau = 8000 \text{ y}$ (high-B approx.)

SGR bursts may result from starquakes due to magnetic stress on NS crust.

Kouveliotou et al. 1998

http://science.msfc.nasa.gov
Neutron star structure

- EOS - what is happening in the inner core? Pion condensates? Solid n? Quark matter?

http://science.msfc.nasa.gov
Radius Determination

- Blackbody spectral fits to X-ray bursts yield photospheric radii of ~10-20 km (using globular cluster sources with known distances). Uncertainties: deviations from blackbody spectra, photospheric expansion, $L_{\text{accr}}$ spectra

- $r_{\text{ms}} =$ radius of marginally stable orbit $= 6GM/c^2$ for Schwarzschild metric, varies from $GM/c^2$ to $9GM/c^2$ for Kerr metric with maximal prograde to retrograde orbits.

- Highest kHz QPOs in NS are all ~1100 Hz (>8 sources): interpret this as Keplerian orbital frequency at $r_{\text{ms}}$

- NS is inside $r_{\text{ms}}$ for almost all EOS: sets limit on $R = 12$ km for $M=1.4 \, M_\odot$ for Schwarzschild metric.

Kaaret, Ford and Chen 1997
Zhang, Strohmayer and Swank 1997
Orbit Determination

- 5 Orbital Elements:

a: semi-major axis
T: time of periastron passage
e: eccentricity
ω: longitude of periastron
i: inclination of orbit
Orbital Determination - non-pulsars

- Use eclipse or dip timing based on Roche-lobe geometry for non-pulsing sources
Orbit Determination - non-pulsars

- Dips are due to gas stream - variable intensity
- Eclipses are due to companion star - constant intensity but short due to high inclination angles

4U 1822-371

EXO 0748-676
Orbit Determination - pulsars

- Track Doppler shifted pulsations for pulsars

\[ t_n = t_o + nP + n^2 P \dot{P}/2 \]
\[ + f(a, i, \omega, T, e) \]
\[ + \ldots \]

Fit 5 orbital elements as well as \( P \) and \( \dot{P} \) using either arrival times or cross-correlated pulse phases.

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ADXRS p. 14
Orbit Determination - pulsars

circular, eclipsing
HMXB SMC X-1

eccentric, non-eclipsing
Be transient 4U0115+63

ADXRS p. 15
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ADXRS p. 16
Orbits for LMXBs

Most orbits for LMXBs are determined through studies of optical modulation. Eclipses in LMXB were discovered by Cominsky and Wood (1984), following many studies of “dippers”.

[Diagram of orbits for LMXBs]
Orbits for X-ray Binary Pulsars

Eclipses

Be "transients"

Eccentric

NEUTRON-STAR ORBIT AND COMPANION-STAR MASS FOR A NUMBER OF BINARY SYSTEMS
Orbital Evolution

- Typical $\dot{P}_{\text{orb}}/P_{\text{orb}}$: $10^{-6}$ for HMXB, $10^{-10}$ for LMXB
  - about the same as $\dot{M}$ in $M_\odot$ y$^{-1}$
- EXO 0748-676 has $\dot{P}_{\text{orb}} > 10^2$ too large for evolution

EXO0748-676

Orbital Period Changes in Cen X-3

Kelley et al. 1983

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Mass Determination - Neutron Stars

- All pulsing neutron stars are consistent with 1.4 $M_\odot$
- EOS-independent relation from kHz QPOs:
  \[ \frac{M_{\text{NS}}}{M_\odot} = \frac{2198}{\nu_{\text{max}}} \text{ Hz} \]

\[ M_{\text{NS}} = 2.0 \, M_\odot \]
(assumes upper kHz QPO is Keplerian orbital frequency at $r_{\text{ms}}$)

Consistent with accretion for $10^8$ y at 10% $L_{\text{edd}}$ onto 1.4 $M_\odot$ initial NS mass from supernova

Kluzniak, Michelson and Wagoner 1990
Kaaret, Ford and Chen 1997
Zhang, Strohmayer and Swank 1997
Mass Determination - Black Holes

- Black holes are more difficult - depends on radial velocity curve and spectral type of companion, plus limits on inclination from ellipsoidal light variations.

Any unseen, non-pulsing, non-bursting object with mass function greater than $3 \, M_\odot$ is a candidate black hole. Other common characteristics are two-component spectra and very strong transient outbursts.

For Cyg X-1: $M_x = 16 \pm 5 \, M_\odot$
Best BHC masses are for “X-ray novae” - optical studies done in quiescence are not contaminated by light from the accretion disk. There are 8 well-studied X-ray novae: best case is V404 Cyg, where the mass function (lower limit on BH mass) \( f(M/M_\odot) = \frac{PK^3}{2\pi G} = 6.08 \pm 0.06 \), where \( K \) is the radial velocity in km s\(^{-1}\).
Microquasars

- Two superluminal galactic sources with radio jets and transient, highly variable X-ray emission: GRS1915+105 and GRO J1655-40.

\[ M \sim 10^6 \, M_\odot \]
\[ R_{\text{disk}} \sim 10^9 \, \text{km} \]
\[ T_{\text{disk}} \sim 10^3 \, \text{K} \]

UV/optical
\[ R_{\text{lobe}} \sim 10^6 \, \text{lt-y} \]

X-rays
\[ M \sim 10 \, M_\odot \]
\[ R_{\text{disk}} \sim 10^3 \, \text{km} \]
\[ T_{\text{disk}} \sim 10^7 \, \text{K} \]
\[ R_{\text{lobe}} \sim 10 \, \text{lt-y} \]
Mass Determination - Black Holes

- QPOs from BHCs vary from 6 - 300 Hz. If Keplerian orbital frequency at $r_{\text{ms}}$ for Schwarzschild BH, then mass of GRS1915+105 $\sim 33 \, M_\odot$, and for GRO J1655-40 $\sim 7 \, M_\odot$, which agrees with its dynamical mass (Morgan, Remillard and Greiner 1997, Orosz and Bailyn 1997).

- Diskoseismic model has eigenfrequencies of radial disk modes that are $f(M, J)$ of BH. Predicts $\sim 11 - 36 \, M_\odot$ for GRS1915+105 (Schwarzschild to maximal Kerr) (Nowak et al. 1997).
Advection dominated accretion flow (ADAF) models of Narayan et al. give good results for optical to X-ray spectra of X-ray transients in quiescence. In ADAF, most of the viscous heat in the accretion disk is carried with the gas and only a small fraction is radiated. When the flow reaches the compact object, it either heats the surface of the NS ($\eta = 10\%$) or disappears over the event horizon of the BH ($\eta = 0.05\%$).

Prediction: BH X-ray novae will have a larger $L_{\text{max}}/L_{\text{min}}$ than NS X-ray transients, as $L_{\text{min}}$ will be much lower for a given accretion rate. Dynamic range for BH $\sim 10^2 \times$ NS.
Observations of the “ultra-soft” component in many BH spectra is interpreted as blackbody emission from inner disk at $r_{ms}$. BB spectral fits to $L$, $T$ can be used to classify BHCs on the basis of spin:

- extreme prograde (maximal Kerr) $\eta = 30\%$, $r_{ms}/(GM/c^2) = 1$
- slowly or non-rotating (Schwarzschild) $\eta = 6\%$, $r_{ms}/(GM/c^2) = 6$
- extreme retrograde $\eta = 3\%$, $r_{ms}/(GM/c^2) = 9$

Microquasars, which have harder spectra, are found to be extreme prograde, with spins between 70-100% of maximal rate.

Strong “ultra-soft” emitters are non-rotating BHs.

BHCs that have no detectable “ultra-soft” emission are extreme retrograde BHs, as the emission has gotten too soft for the X-ray bandpass.
Relativistic Effects: frame-dragging

- Stella and Vietri (1998) first proposed the Lense-Thirring effect to explain ~20 Hz QPOs in LMXBs with kHz QPO “twin peaks”. Assumes beat frequency model, NS spin is kHz difference frequency. Orbital plane of test particle is tilted with respect to spin axis of NS. Weak field approx:

\[ \nu_{LT} = \frac{8\pi^2 I v_K^2 v_s}{M c^2} = 13.2 I_{45} M_0^{-1} \nu_{K3}^2 \nu_{s2.5} \text{ Hz} \]

where:

- \( I_{45} \) = moment of inertia in units of \( 10^{45} \text{ g cm}^2 \), \( M_0 \) = mass in solar units,
- \( \nu_{K3} \) = Kepler frequency in kHz, \( \nu_{s2.5} \) = spin frequency in units of 300 Hz.

- Cui, Zhang and Chen (1998) extended this explanation to include the microquasar BHCs in the strong field limit, for different values of angular momentum and tilt angle. The BHC QPOs are then interpreted as X-ray modulation at the disk precession frequency due to frame-dragging.
Disk Jet Interaction

- Coordinated IR/RXTE observations of GRS 1915+105
  - X-ray and IR are correlated at the beginning of flares
  - X-ray and IR flares have constant offset
  - IR then decouples from X-ray, which oscillates wildly
  - IR, Radio emission is non-thermal

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Eikenberry et al. 1998
Gravity Waves from Rotating NS

Two new predictions of “observable” Gravity Waves (GW) from rotating neutron stars:

- Owen et al. (1998) - time-varying quadrupole from unstable r-modes couple to gravitational radiation through current multipoles, force spin to ~100 Hz immediately after birth of hot young NS. Increases prospects for GW burst detection from supernovae.

- Bildsten (1998) - misaligned temperature gradient creates time varying quadrupole. Resulting spin down by GW emission competes with spin up from accretion to keep NS rotation at ~300 Hz in LMXBs. Detect GW at $h_c \sim 2 \times 10^{-26}$ from Sco X-1 in 1 y!
Summary

- Detailed X-ray observations of NS and BH have provided precise measurements of physical parameters for these compact objects.
- General relativistic effects are being observed and are yielding information about the metric.
- Future observations may be able to test predictions of GR in strongest possible gravitational fields.
Where to get more information

- Bender et al. 1995 SLAC-PUB-95-6915 (Snowmass 94)
- Bildsten 1998, astro-ph 9801043, 9804325
Where to get more information

- Lindblom, Owen and Morsink 1998 gr-qc 9803053 and Owen et al. 1998 gr-qc 9804044