X-ray Bursts: Nuclear Physics on Neutron Stars

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Some Motivation

• Why might a nuclear physicist be interested in accreting neutron stars (in particular, X-ray bursts)? (and vice versa!).

• Accreting neutron stars reveal observable manifestations of nuclear physics (X-ray bursts, superbursts, crust cooling-heating and related phenomena). These, in principle, can tell us both about fundamental physics (including nuclear physics) and neutron stars, though extracting all the information will be a challenge.

• Neutron stars probe physical regimes beyond that obtainable in a laboratory. Nuclear symmetry energy, equation of state, existence of new states of matter, gravitational physics.

• I will summarize some recent efforts to do this, using X-ray observations of accreting neutron stars.
Plan For Lectures

Part 1: Introduction, X-ray burst basics, comparisons with observations, new recent results.

Part 2: Moving away from Spherical Symmetry, timing observations, neutron star spin, burst ignition and spreading.

Part 3: Superbursts, X-ray probes of neutron stars; mass-radius constraints, X-ray pulsar and eclipse timing, pulse profile fitting, spectroscopy, recent results and status.

Part 4: Future prospects, missions in planning and development, summary.
Neutron Stars: A (very) Brief Introduction and History

- Neutron stars, existence predicted in the 1930’s, Zwicky & Baade (1933), super-nova, neutron first discovered in 1932 (Chadwick).

- Theoretical properties and structure, Oppenheimer & Volkoff (1939), TOV eqns.


- First firm observational detection, discovery of radio pulsars, 1967 (Bell & Hewish). Hewish wins Nobel Prize in 1974, Bell does not.

- Binary Pulsar discovered, 1974, Hulse-Taylor win Nobel Prize, 1993, gravitational radiation

Neutron Stars: Nature’s Extreme Physics Labs

- Neutron stars, ~2 Solar masses compressed inside a sphere ~20 km in diameter.
- Highest density matter observable in universe.
- Highest “persistent” magnetic field strengths observable in the universe.
- General Relativity (GR) required to describe structure. Complex Physics!!
- All forces needed!
The Neutron Star Equation of State

Demorest & Ransom 2011

- High mass measurements, limit softening of EOS from hyperons, quarks, other exotic stuff.
- Most good mass measurements at low end, and systems not conducive to radius estimates, EOS not constrained strongly.
- Need either masses for higher mass systems (accretors), and/or possibility to get R (AMPs).
Neutron Star Radii and the Equation of State

• $R$ weakly dependent on $M$ for many EOSs.

• Precise radii measurements alone would strongly constrain the EOS.

• Radius is prop. to $P^{1/4}$ at nuclear saturation density. Pressure largely related to density dependence of symmetry energy of nuclear interaction (isospin dependence).

• More reliable in absence of softening.
Rotating Neutron Stars

- Rotation: Increases maximum mass, centrifugal support. Max spin rate, mass shedding limit, depends on EOS (Cook, Shapiro, Teukolsky 1994).

- Rotation: Equatorial bulge, increases radius at rotational equator. Effective gravity is now function of latitude.
Compact Stars, Accretion Power

- Visualization of an accreting neutron star binary.

- **Accretion Powered:** X-ray binaries
  - X-ray Binaries: neutron star or black hole with normal star.
  - Accretion powers X-ray emission.

- **Nuclear Powered:** X-ray burst sources (neutron stars only).

\[ E_{\text{grav}} = \frac{GMm}{R} = \left(\frac{GM}{c^2R}\right) mc^2 \sim 0.2 mc^2 \sim 200 \text{ MeV} \]

per baryon \( \implies T \sim \text{few} \times 10^7 \text{ K} \sim \text{keV range, X-rays!} \)

Credit: Rob Hynes (binsim)
Sources of Thermonuclear Bursts: LMXBs Containing Neutron Stars

http://www.sron.nl/~jeanz/bursterlist.html

- Accreting neutron stars in low mass X-ray binaries (LMXBs).
- Approximately 100 burst sources are known.
- Concentrated in the Galactic bulge.
- Bursts triggered by thermally unstable H or He burning at column of few x $10^8$ g cm$^{-2}$
- Liberates $\sim 10^{39} - 10^{43}$ ergs. First discovered 1976 (Grindlay et al., Belian et al. 1976)
- Recurrence times of hours to a few days (or years).

Fun fact: a typical burst is equivalent to 100, 15 M-ton ‘bombs’ over each cm$^2$!!
Accreting Neutron Star binaries: what do we see?

Accretion of matter converts gravitational potential energy to radiation (X-rays, persistent flux).

Can produce normal bursts (recur hours to days) and superbursts (years).

\[ Q_{\text{H,solar}} \approx 5 \text{ MeV}, \quad Q_{\text{He}} \approx 1.6 \text{ MeV} \]

\[ \alpha \equiv \frac{\int_0^{\Delta t} F_p \, dt}{\int_0^{\Delta t} F_b \, dt} \approx \frac{(GM/R)}{Q_{\text{nuc}}} \]
“Normal” Thermonuclear Bursts

- 10 - 200 s flares.
- Thermal spectra which soften with time.
- 2 - 18 hr recurrence times, sometimes quasi-periodic.
- \( \sim 10^{39} \) ergs
- H and He primary fuels.

He ignition at a column depth of \( 2 \times 10^8 \) g cm\(^{-2} \)
Bursts and Nuclear Burning: Theory

- Accreted layer, and pressure scale height, \( h \ll R \), so local, plane-parallel analysis OK.
- What is the fate of a mass element as it is buried and compressed?

\[
L_{\text{acc}} = \frac{G M m}{R}, \quad m_{\text{Edd}} \sim 1.7 \times 10^{-8} M_\odot \text{ yr}^{-1}, \text{ local rate of, } m_{\text{Edd}} / 4\pi R^2 = m_{\text{Edd}} = 8.6 \times 10^4 \text{ g cm}^{-2} \text{ s}^{-1}
\]

Accreted matter is H and He rich with likely mix of metals (exact composition, \( Z \), usually uncertain!). \( T \) almost always \( > \) few \( \times 10^7 \) K

**==>** Hot (beta-limited) CNO cycle dominates H burning.
CNO H burning

Thanks to Alex Heger!
Burst Theory Con’t

Hot CNO cycle, Fowler & Hoyle (1965)

\[ ^{12}\text{C}(p, \gamma)^{13}\text{N}(p, \gamma)^{14}\text{O}(\beta^+)^{14}\text{N}(p, \gamma)^{15}\text{O}(\beta^+)^{15}\text{N}(p, \alpha)^{12}\text{C}, \]

- For \( \dot{m} > 900 \text{ g cm}^{-2} \text{ s}^{-1} (Z_{\text{CNO}}/0.01)^{1/2} \), temperatures and densities in the accumulating layer are such that the proton captures proceed more rapidly than the \( \beta \) decays, leading to thermal stability (an increase in temperature does not raise the energy generation rate, which is limited to, \( \varepsilon \sim 6 \times 10^{15} (Z_{\text{CNO}}/0.01) \) ergs g\(^{-1}\) s\(^{-1}\) (Fujimoto, Hanawa & Miyaji 1981; Fushiki & Lamb 1987; Cumming & Bildsten 2000; Cooper & Narayan 2007).

- EXERCISE: Show that the time to burn all the H in a fluid element is about a day (for \( Z_{\text{CNO}} = 0.01 \), and \( X_0 = 0.7 \)).

- At lower \( \dot{m} \) the CNO cycle becomes temperature sensitive and H burning can trigger instability.
**Burst Ignition: Thin Shell Instability**

- Bursts caused by thin shell thermal instability, Schwarzchild & Härm (1965), Hansen & Van Horn (1975).

- Ignition at: \( \frac{d\varepsilon_{\text{nucl}}}{dT} > \frac{d\varepsilon_{\text{cool}}}{dT} \); \( \varepsilon_{\text{cool}} \propto T^4 \) (radiative cooling of thin shell). Strong T-dependence of triple-alpha reaction can induce ignition.

- **H, He burning stabilizes** (no bursts).
  - He ignition in a mixed H/He shell (case I).
  - He ignition in a pure He environment (case II).
  - H ignition in a mixed H/He environment (case III).

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Cumming & Bildsten (2000)
Mixed H/He Burning: rp Process

- For mixed H/He burning with He ignition, the ignition column does not depend strongly on $\dot{m}$, $\Rightarrow$ $t_{\text{rec}} \propto \dot{m}^{-1}$ (case I, $\dot{m} > 2,000 \text{ g cm}^{-2} \text{ s}^{-1}$)

- For pure He shell burning, the ignition column decreases as $\dot{m}$ increases, so $t_{\text{rec}}$ drops more steeply, $\propto \dot{m}^{-3}$ (case II, $900 \text{ g cm}^{-2} \text{ s}^{-1} < \dot{m} < 2,000 \text{ g cm}^{-2} \text{ s}^{-1}$)

- Above rates are with $Z_{\text{CNO}} = 0.01$

- H burning proceeds via $\alpha p$ and rp-processes (rapid proton captures and betas).
- Increases and delays the energy release $\Rightarrow$ longer light curves.

(Schatz, Bildsten, & Cumming 1999)  (Schatz et al. 2001)
X-ray Bursts: Nuclear Physics and Burst Profiles

- Multi-zone numerical hydro models with sophisticated reaction networks (Woosley et al. 2004)

- Uncertainties of rp-process reaction rates can dramatically affect light curves.
Marginally Stable Burning: mHz Oscillations

\[ f \propto \frac{\delta T}{T} \]
\[ \alpha = \frac{d\ln(\varepsilon)}{d\ln(T)} \]

**EXERCISE:** Show that for a one-zone model the temperature fluctuations satisfy the equation for a damped harmonic oscillator (van der Pol oscillator).

- Typically \( t_{\text{therm}} \ll t_{\text{accr}} \), and the middle term dominates (bursts). But near stability \( (\alpha \approx 4) \) the oscillatory term can dominate (oscn’s with \( \omega^2 = \frac{2\alpha}{t_{\text{accr}} t_{\text{therm}}} \))

- Multi-zone modeling (Heger et al. 2007) shows mHz QPOs with few minute periods.

- Periods sensitive to surface gravity, H fraction! Potential probes of these quantities.

Heger et al. (2007)
Launched in December, 1995, science operations concluded on January 5, 2012, after 16 years of discovery! Huge and rich X-ray burst archive.

http://heasarc.gsfc.nasa.gov/docs/xte/xte_1st.html

RXTE’s Unique Strengths

• Large collecting area
• High time resolution
• High telemetry capacity
• Flexible observing
### Last Contact With RXTE Spacecraft

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Data Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>005-17/35/22.5</td>
<td>1604 AARWA4PWR=0 less than YELLOW LOW</td>
<td></td>
</tr>
<tr>
<td>005-17/35/22.6</td>
<td>1604 AAACEAPWR=0 less than YELLOW LOW</td>
<td></td>
</tr>
<tr>
<td>005-17/35/22.6</td>
<td>1604 AAACEBPWR=0 less than YELLOW LOW</td>
<td></td>
</tr>
<tr>
<td>005-17/35/34.1</td>
<td>1644 Telemetry data dropout (15 sec)</td>
<td></td>
</tr>
<tr>
<td>005-17:40:21.9</td>
<td>3207 NCC ACK for message 91/03 has been received</td>
<td></td>
</tr>
<tr>
<td>005-17:40:22.0</td>
<td>3175 NCC COMMUNICATIONS TEST MSG message received</td>
<td></td>
</tr>
</tbody>
</table>

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The Rossi X-ray Timing Explorer (RXTE) is a satellite that observes the fast-moving, high-energy worlds of black holes, neutron stars, X-ray pulsars and bursts of X-rays that light up the sky and then disappear forever.

How fast and how energetic are they? Well, some pulsars spin faster than a thousand times a second. And a neutron star kick is so powerful that its strong gravity can cause a small surface area to hit with the force of a thousand hydrogen bombs. Astronomers study changes that happen from microseconds to months in cosmic objects to learn about how gravity works near black holes, how pulsars in binary systems are affected by mass transferring from one star to the other, and how the giant engines in distant galaxies are powered. RXTE was launched into low-Earth orbit on December 30, 1995, and is still going strong, making unique contributions to our understanding of these extreme objects.
GS 1826-24: A “Textbook” Burster?

- Very steady X-ray flux, and thus mass accretion rate.
- Regular “clocked” bursts (Cocchi et al., Ubertini et al.)
- Long duration and $\alpha \approx 40 \implies$ mixed H/He burning.
- $\dot{m}$ comfortably in the mixed ignition regime
• Recurrence time drops as flux increases with expected $f^{-1}$ behavior

• Drop in $\alpha$ with $f_{\text{per}}$ favors solar-like abundance of CNO. More H present, higher $Q_{\text{nuc}}$ $\Rightarrow$ lower $\alpha$.

• Can “see” the stable CNO burning!
But one zone models with solar abundances over predict the recurrence time and burst fluence.

In these models as $t_{\text{rec}}$ drops less H burning $\Rightarrow$ less He present and ignition mass increases.

Additional heating (thermal inertia from prior bursts).

Maybe local accretion rate changes (fuel covering factor)?

Need more realistic multi-zone, multi-D models.
Detailed multi-zone modeling (Heger et al. 2007) shows that $Z \approx 0.02$ needed to match average burst light curves. Also now matches $t_{\text{rec}}$ (thermal inertia).

Rise light curve does not match precisely. Models show two-stage rise.
GS 1826-24: Multi-zone Modeling and Long Tails

- In ‘t Zand et al. averaged many (~30) bursts from GS 1826, after subtracting off persistent (pre-burst) data. Faint exponential tail evident.

- Multi-zone modeling matches light curve, tail from cooling of deeper layers heated by burning.

in ‘t Zand et al. (2009)
Global Burst Rates: Where are the Bursts at Higher $F_p$?

- Simple theory would predict bursting should continue (though with higher rates and smaller fluences) to the stability regime at $\dot{m} \sim$ Eddington.

- Large samples of bursts (RXTE and BeppoSAX/WFC) suggest burst rates drop, and few bursts seen above $\sim0.2 \dot{m}_{edd}$?
Global Burst Rates: Where Does the Fuel Go?

- Observed persistent flux related to global accretion rate; could the fuel coverage be limited to a portion of the star, so that local rate near stability? Bildsten (2000). Non-spherical behavior. Additional heating would stabilize too.

- What about spin and angular momentum of accreted matter; mixing of accreted fuel? Shear instabilities can mix fuel to deeper, hotter layers, where it could burn stably. Keek et al. (2009), rotationally induced B-fields give strong magnetic diffusivity, lowers accretion rate at which expect stability. Keek, Langer & In ‘t Zand (2009)
New NS Transient in Ter 5: IGR J17480--2446

- New X-ray transient found by INTEGRAL (Oct. 2010), in GC Ter 5.
- Subsequent RXTE observations find 11 Hz pulsar (Strohmayer & Markwardt 2010), and 21.3 hr circular orbit, and extensive thermonuclear behavior.
Aside: Lunar Occultation of IGR J17480--2446 with RXTE

- Precision timing of eclipse ingress and egress (< 10 ms).
- Accurate Lunar ephemerides.
- Lunar topography data.
- Enable sub-arcsecond position determination!

Riggio et al. (2012)

Never underestimate the power of timing!
T5X2: 11 Hz pulsar transient

Linares et al. (2012)
T5X2: 11 Hz Pulsar Transient

- Smooth variation of burst rate with mass accretion rate
- Bursting continued to high $\dot{m}$
- mHz QPOs, marginally stable burning.
- Several burning regimes identifiable.

Linares et al. (2012)
T5X2: 11 Hz pulsar transient

- Several bursting regimes identified, He to H/He (B to C), shows correct $t_{\text{rec}}$ dependence
- However, would need low H to match the inferred transition
- And one-zone models don’t match the short recurrence times and smaller burst energies (Extra Heat?)
Marginally Stable Burning: Observed mHz QPOs

- mHz QPO behavior in 4U 1636-53, when frequency drops below ~8 mHz, then bursting is seen. QPOs at < 0.1 Eddington, Altamirano et al. (2008).
- Inferred accretion rate is again apparently to low for He stability limit by ~ x10.

- QPO frequency in T5X2 lower by factor ~2-3.
- Perhaps behavior in T5X2 is related to He stability limit (matches models), and other sources related to H stability limit?
T5x2 fills a gap in the $B$ – spin frequency distribution for accreting NS
Linares et al. (2012)
Part 2
The end of Spherical Symmetry
Burst Oscillations: Neutron Star Spins

- Discovered in Feb. 1996, shortly after RXTE’s launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.

- 4U 1728-34, well known, frequent burster.
- Power spectra of burst time series shows significant peak at 363 Hz.
Oscillations at Burst Onset

An X-ray burst from 4U 1636-53 with 1.7 ms oscillations.
Timing and Spectral Evidence for Rotational Modulation

- Oscillations at onset caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

Strohmayer, Zhang & Swank (1997)
Coherence of Burst Oscillations

4U 1702-429: Strohmayer & Markwardt (1999)

Burst oscillations generally have high coherence (Q > 4,000)

exponential recovery in some bursts.

Model:  \[ f(t) = f_0 \left( 1 - \delta e^{(-t/\tau)} \right) \]
Bursts from 4U 1728-34 separated by ≈ 16 years have the same asymptotic oscillation frequency.

Indicative of highly stable process such as rotation.

Nuclear-powered pulsars.
**SAX J1808.4-3658: The First Accreting Millisecond Pulsar**

- Source first discovered in 1996 with BeppoSAX, LMXB burster (in ‘t Zand et al. 1998).
- New outburst in 1998 found with RXTE/PCA
- Subsequent observations reveal binary millisecond pulsar (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998)

- 401 Hz pulsar
- 2 hr orbital period
- Low mass companion (~0.1 \( M_{\text{sun}} \))
X-ray Bursts from Accreting ms Pulsars: SAX J1808 and XTE J1814-338

SAX J1808: Chakrabarty et al. (2003)

XTE J1814-338: Strohmayer et al. (2003)
NS Spin Distribution: A Speed Limit for Neutron Stars?

- RXTE pulsation sensitivity extends well above NS break-up limit, but no spin detection above 620 Hz
- If intrinsic distribution were flat out to break-up (2 kHz), then expect to see some sub-ms pulsars, ==> ~730 Hz cutoff (Chakrabarty et al. 2003). Highest spin frequency 716 Hz (Hessels 2007).

TABLE 7
ACCRETION AND NUCLEAR POWERED MILLISECOND PULSARS

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Spin Frequency [Hz]</th>
</tr>
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<tbody>
<tr>
<td>Swift J1756-2508</td>
<td>182</td>
</tr>
<tr>
<td>XTE J0929-314</td>
<td>185</td>
</tr>
<tr>
<td>XTE J1807-294</td>
<td>190</td>
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<tr>
<td>NGC 6440</td>
<td>205</td>
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<tr>
<td>IGR J17511</td>
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<tr>
<td>IGR J1719-2821</td>
<td>294</td>
</tr>
<tr>
<td>MXB 1730-335</td>
<td>306</td>
</tr>
<tr>
<td>XTE J1814-338</td>
<td>314</td>
</tr>
<tr>
<td>4U 1728-34</td>
<td>363</td>
</tr>
<tr>
<td>HETE J1900.1-2455</td>
<td>377</td>
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<tr>
<td>SAX J1808.4-3658</td>
<td>401</td>
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<tr>
<td>4U 0614+09</td>
<td>415</td>
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<tr>
<td>XTE J1715-305</td>
<td>435</td>
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<tr>
<td>SAX J1748.9-2021</td>
<td>442</td>
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<td>SAX J1749.4-2807</td>
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<td>KS 1731-260</td>
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<td>Aql X-1</td>
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<td>EXO 0748-676</td>
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<td>MXB 1659-298</td>
<td>556</td>
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<td>4U 1636-536</td>
<td>581</td>
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<td>IGR J00291-5934</td>
<td>599</td>
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<tr>
<td>SAX J1750.8-2900</td>
<td>601</td>
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<tr>
<td>4U 1608-52</td>
<td>620</td>
</tr>
</tbody>
</table>

Patruno (2010)
Ignition: Extreme Weather on Neutron Stars

- Burst heating and Coriolis force drive zonal flows; vortices and retrograde flows may account for late time asymmetry and frequency drifts.
- Cross front circulation (ageostrophic)
Burst Oscillations: Ignition and Spreading

- Rotation allows for “confinement” of the hot-spot, “Rossby adjustment radius.”

- Localized nuclear heating drives transverse pressure gradients, coupled with spin (coriolis force) leads to “nuclear hurricanes.”

- Similarity with weather systems, pressure gradients balanced by coriolis forces (geostrophic balance).

- Front speed depends on latitude, slower at the poles.

Thanks to Anatoly Spitkovsky!
Amplitude evolution during burst rise encodes information on nature of flame spreading.

Some bursts show high initial amplitude, rapid decrease, and then persist at lower amplitude.
Coriolis Force influences spreading speed

• Spitkovsky, Levin & Ushomirsky (2002) showed Coriolis force relevant to ignition and spreading.

• Flame speed faster at equator, slows with increasing latitude.

Modelling of near-equatorial ignition, and Coriolis dependent spreading, can better explain amplitude evolution of some bursts.

Bhattacharyya & Strohmayer (2007)
Photospheric Radius Expansion

- Local atmospheric flux can reach Eddington limit.
- Radiation pressure drives wind, expands photosphere.
- Models indicate L stays constant. R increases, Teff drops, spectrum softens.

Double-peaked bursts: A Spreading Phenomenon?

- A small fraction of bursts show multiple peaks NOT associated with photospheric radius expansion (4U 1636-53, a famous example).

- These are sub-Eddington in peak flux.

- Several models proposed: 1) shear instability (Fujimoto): 2) “Delayed” nuclear energy release (Fisker et al.).

- All of these “one dimensional” in some sense

Bhattacharyya & Strohmayer (2005)
Double-peaked bursts: A Spreading Phenomenon?

- We explore spreading in a manner analogous to Spitkovsky et al (2002).
- Using fully relativistic model of photon propagation from NS surface (Bhattacharyya et al. 2005).
- Spreading from equator appears implausible.
- Spreading from a pole with front “stalling” near equator can qualitatively explain observed properties.

Bhattacharyya & Strohmayer (2005)
A Double-peaked Burst with Oscillations: Evidence of Stalling?

- An unusual double-peaked burst from 4U 1636-53 shows 582 oscillations during the first (weaker) peak.
- A spreading model can account for double peaks, and oscillations, but ignition must be at high latitude (but not the pole).
- Stalling of the front required again. Some indications for this in the behavior of R.

Bhattacharyya & Strohmayer (2006)