Two Spectral States of Gamma-Ray Emission from Galactic Black Hole Binaries

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• Observations of Galactic black hole transients with the OSSE instrument on Compton GRO
  – Seven transients
    • J0422+32, 1009-45, 1543-45, 1655-40, GX339-4, 1716-249, and 1915+105
  – Focus of the talk
    • Two gamma-ray spectral states and their correspondence with X-ray states
    • Long-term variability
  – Brief discussion
    • Limits on line emission
    • Timing noise properties
    • But first, the instrument…
OSSE instrument on Compton GRO

- **Specifications**
  - Four identical NaI/CsI phoswich detectors
  - Sensitive 0.04 – 10 MeV
  - Total effective area ~2000 cm² at 0.511 MeV
    - 7”-thick phoswich
  - Field of view 3.8° × 11.4°
  - Time resolution
    - 8 - 32 seconds (full energy coverage)
    - 0.125 ms (limited energy coverage)

- **Operating Mode**
  - Each detector independently steerable about one axis (in the narrow FOV direction)
  - Background estimated by chopping on and off the source region on 2-min. time scale
    - Large internal background properly subtracted, low systematics

- **Limitations**
  - Source confusion (src and bkg fields)
  - Lack of imaging
  - Large FOV for point source studies
  - Small FOV for Galactic diffuse line emission

Proposed Feb 1978
Launched Apr 1991
De-orbited Jun 2000
Seven galactic BHB transients
  - All but 1716-249 have good dynamical mass estimates

BATSE lightcurves
  - 20-100 keV
  - 1 Crab = 0.32 cm\(^2\) s\(^{-1}\)

OSSE observations
  - Indicated by gray bands
  - Durations range from ~24 hrs to several weeks, depending on the source
    - What does this do to spectral shape? Any biases?
- Photon spectrum of each BHC
  - Average spectrum over all observing days
    - Note arbitrary scaling factor
  - Two gamma-ray spectral shapes are apparent

- X-ray data for context
  - Contemporaneous
    - J0422+32: TTM and HEXE
    - B1716-249: ASCA
  - Non-contemporaneous
    - J1655-40: ASCA
    - B1009-45: ASCA

Grove et al. 1998 ApJ 500 899
Two gamma-ray spectral states

- Spectral energy density
  - Power law $\gamma$-ray spectrum
    - Associated with
      - X-ray Thermal state (was high / soft)
      - X-ray Steep Power Law state
    - $T_{BB} \sim 1$ keV
    - $\Gamma \sim 2 - 3$
    - No HE break
      - $E_{\text{break}} > 690$ MeV in J1655-40
  - Breaking $\gamma$-ray spectrum
    - Associated with
      - X-ray Hard state (was low / hard)
    - $\Gamma_x \sim 1 - 2$
    - $E_{\text{break}} \sim 50$ keV
    - $E_{\text{fold}} \sim 100$ keV

Grove et al. 1998 ApJ 500 899
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Grove et al. 1998 ApJ 500 899
Spectral summary

- Summary of best-fit spectral model parameters for all seven BHBs
  - GRS 1716-249 is seen in both states
  - GRO J0422+32 is brightest among those with breaking γ-ray spectrum
  - GRO J1655-40 is brightest among those with power law, sets most stringent limit on minimum break energy

<table>
<thead>
<tr>
<th>Best-Fit Model Parameters</th>
</tr>
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<tbody>
<tr>
<td>Object</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Breaking Gamma-Ray State</td>
</tr>
<tr>
<td>GRO J0422+32 .................</td>
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<tr>
<td>GX 339–4 ..................</td>
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<tr>
<td>GRS 1716–249 ...............</td>
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<tr>
<td>Power-Law Gamma-Ray State</td>
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<tr>
<td>GRS 1009–45 .................</td>
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<tr>
<td>4U 1543–47 ..................</td>
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<tr>
<td>GRO J1655–40 ...............</td>
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<tr>
<td>GRS 1716–249 ................</td>
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<tr>
<td>GRS 1915+105 ...............</td>
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</tbody>
</table>

Note—Fits are performed over sum of entire data set for each object for which there was detectable emission, except for GRO J0422+32, where the fit is for the contemporaneous HEXE and OSSE observation, and for GRS 1716–249, where the fit is performed separately for the sum of observations in each spectral state (see text). Errors are 68% confidence. Lower limits on exponential folding energies are 95% confidence. Upper limits on break energies are set at OSSE threshold for spectroscopy. Luminosity is for energies above 50 keV. Ranges for spectral index, folding energy, and luminosity from daily fits are given in the columns labeled by $\Delta \Gamma$, $\Delta E_{\text{fold}}$, and $\Delta L_{\gamma}$. 
OSSE Black Hole States -- Grove

Limits on line emission

• OSSE was much more sensitive than previous instruments reporting lines
  – Recall SIGMA reported broadened 480 keV line at 60 x 10^{-4} ph cm^{-2} s^{-1} from XN Mus 1991 for final 13 hours of observation. Suggestion of backscatter at 170 keV.
  – Leptonic jets might give pair annihilation in a cool medium…
  – No statistically significant narrow or moderately broadened line emission is observed at any time from any of these seven BHBs

<table>
<thead>
<tr>
<th>Source</th>
<th>Line Centroid</th>
<th>FWHM (keV)</th>
<th>Flux (x10^{-4} cm^{-2} s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(keV)</td>
<td>(keV)</td>
<td>5σ upper limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Daily</td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>170</td>
<td>3</td>
<td>&lt;6.3</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>35</td>
<td>&lt;9.3</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>25</td>
<td>&lt;7.5</td>
</tr>
<tr>
<td></td>
<td>511</td>
<td>3</td>
<td>&lt;7.2</td>
</tr>
<tr>
<td>GRO J1655-40</td>
<td>170</td>
<td>3</td>
<td>&lt;5.1</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>35</td>
<td>&lt;7.2</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>25</td>
<td>&lt;6.2</td>
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<td></td>
<td>511</td>
<td>3</td>
<td>&lt;6.1</td>
</tr>
</tbody>
</table>
Concentrate on two best examples

- BATSE lightcurves throughout CGRO mission
  - 20-40 keV flux in Crab units
  - 10-day sums over entire 9-year mission

- Best examples of breaking and power-law gamma-ray spectra
X-ray hard state

• GRO J0422+32, best example of X-ray hard state
  – History
    • Discovered by BATSE (Aug 92)
    • Observed by OSSE for 34 days, ASCA, ROSAT, and Mir/TTM+HEXE
  – Optical counterpart (M dwarf at 2.4 kpc)
    • Mass of primary ~ 3.7 – 5.0 Ms (Filippenko et al. 1995)
  – Transient radio source
    • Synchrotron bubble (Han & Hjellming 1992)
  – Hard X-ray / gamma-ray spectrum
    • Mir-Kvant + OSSE
      – Optically thin thermal Comptonization (i.e. exponentially truncated power law)
      – No need for reflection
    • Luminosity is anticorrelated with temperature (i.e. folding energy)
      – Spectrum hardens (folding energy increases) as source decays
    • No narrow or broad annihilation line features
X-ray hard state

- GRO J0422+32 timing analysis
  - Red noise with two break frequencies
    - Shot noise model gives ~50 ms and ~2.2 sec decay times
  - Peaked noise at 0.04 Hz and 0.23 Hz
    - 0.04 Hz peak is broad, and amplitude varies with time
    - 0.23 Hz peak is broad and asymmetric
      - Well-defined lower freq edge sets max timescale for process that produces the peaked noise
X-ray hard state

• GRO J0422+32 timing analysis
  – Hard photons lag soft photons
    • Frequency-dependent lag
    • ~1 ms to ~300 ms
  – Long timescales and time lags
    • Imply that the $\gamma$-ray emitting region is much larger than last stable orbit
    • Frequency-dependent lags may suggest large Comptonizing cloud with density proportional to $1/r$
      – See Kazanas, Hua, Titarchuk (1997)
  – Recall
    • Soft band = 35-60 keV
    • Hard band = 75-175 keV
X-ray thermal or steep power law state

- GRO J1655-40, best example of X-ray thermal or steep pwr law state
  - History
    - Discovered by BATSE (July 94)
    - Observed by OSSE for 32 days, ASCA, GRANAT/WATCH
  - Optical counterpart (F type at 3.2 kpc)
    - Mass of primary ~ 6.0 – 6.6 Ms
    - Eclipses at 2.6 d imply viewed nearly edge on (Bailyn et al. 1995a,b)
  - Strong radio source (Tingay et al. 1995, Hjellming & Rupen 1995)
    - Superluminal radio jet
    - Ejection follows hard X-ray flares (Harmon et al. 1995)
  - Hard X-ray / gamma-ray spectrum
    - OSSE: Simple power law up to or beyond ~600 keV
      - Photon index 2.6 – 3.0
      - Exponential cutoff $E_{\text{break}} > 690$ keV (95% confidence)
    - No narrow or broad annihilation line features
    - Gamma-ray variability
      - One instance of factor-of-2 on hourly timescales
Multiple observations

Summary of observations:

<table>
<thead>
<tr>
<th>Object</th>
<th>Observation Dates</th>
<th>MJD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRO J1655-40</td>
<td>1994 Aug 4-9</td>
<td>49568 - 49573</td>
</tr>
<tr>
<td></td>
<td>(1994 Aug 29-31)</td>
<td>49593 - 49595</td>
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<tr>
<td></td>
<td>1994 Dec 7-13</td>
<td>49693 - 49699</td>
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<tr>
<td></td>
<td>1995 Mar 29 - Apr 4</td>
<td>49805 - 49811</td>
</tr>
<tr>
<td></td>
<td>(1996 Mar 18-21)</td>
<td>50160 - 50163</td>
</tr>
<tr>
<td></td>
<td>1996 Aug 27 - Sep 6</td>
<td>50322 - 50332</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>1995 Nov 21 - Dec 7</td>
<td>50042 - 50058</td>
</tr>
<tr>
<td></td>
<td>1996 Oct 15-29</td>
<td>50371 - 50385</td>
</tr>
</tbody>
</table>

Spectral parameters

Daily and total energy spectra are well described by simple power law with photon index $\Gamma$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Mean $\Gamma$</th>
<th>$\Gamma$ Range</th>
<th>Mean $L_\gamma$ ($\times 10^{36}$ erg/s)</th>
<th>$L_\gamma$ Range ($\times 10^{36}$ erg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRO J1655-40</td>
<td>2.76 ± 0.01</td>
<td>2.6 - 3.0</td>
<td>6.1</td>
<td>5.1 - 9.5</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>3.08 ± 0.06</td>
<td>2.9 - 3.3</td>
<td>31.</td>
<td>27. - 45.</td>
</tr>
</tbody>
</table>
• Average spectral energy density
  - $\Gamma = 2.76 \pm 0.01$
  - $E_{\text{break}} > 690$ keV (95% confidence)
  - Full dataset
Spectra in individual ~1-week observations

- Hardness anti-correlated with 50-100 keV flux (weaker are harder)

Kroeger et al. 1996 A&AS
• OSSE lightcurve
  – 45-100 keV flux (c/s)
    • One datapoint per GRO orbit
  – Note factor-of-two (point 5) decline over 94/245-249
  – Any spectral change?

GRO J1655-40 lightcurve

Starts TJD 10322
During the four days of declining 45-100 keV flux…

- Some change in spectral hardness
- One datapoint per s/c orbit

- Spectrum hardens as soft flux decreases
  - Trend on ~90 min timescales is consistent with trend on ~weekly timescales
  - Of course, a portion of this decline does not follow that trend
Flux v. hardness relation

- For that entire week, adding days not in the decline
  - One point per s/c orbit
  - The total spectrum is certainly a mix of spectra with differing hardness

- For all OSSE data
  - Each day
    - Consistent with power law
  - Each week
    - Emission above 500 keV
  - Average $L_\gamma$
    - $6.1 \times 10^{36} \text{ erg s}^{-1}$
  - Range of $L_\gamma$
    - $(5.1 - 9.5) \times 10^{36} \text{ erg s}^{-1}$
Summary

• Study of transient and persistent black hole binaries observed by Compton GRO OSSE instrument
  – Two spectral states above 50 keV are apparent
    • Hard Comptonized continuum with $E_{\text{break}} \sim 50$ keV and $E_{\text{fold}} \sim 100$ keV
      – Same as “X-ray hard” state
      – Strong timing noise
    • Softer power law ($\Gamma \sim 2 – 3$) with no evidence of high $E$ break
      – Same as “X-ray thermal” or “steep power law” state
      – $E_{\text{break}} > 690$ keV for GRO J1655-40
        » This requires summing over ~30 days, with $L_\gamma$ ranging by nearly factor of two
        » Spectral hardness is sometimes anti-correlated with $L_\gamma$
        » Evidence for emission >500 keV on weekly timescales
        » No evidence for deviation from simple power law on shorter timescales
      – Weak timing noise
Appendix

- Summary of phenomenology of all seven BHBs

<table>
<thead>
<tr>
<th>OBJECT</th>
<th>ULTRASOFT COMPONENT?</th>
<th>$L_x (&gt; 50$ keV) $(\times 10^{36}$ ergs s$^{-1}$)</th>
<th>LIGHT CURVE TYPE</th>
<th>TIMING NOISE?</th>
<th>RADIO EMISSION?</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
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<td>$&lt;20$ keV</td>
<td>$&gt;50$ keV</td>
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<tr>
<td>Breaking Gamma-Ray State</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>No$^a$</td>
<td>14.0–26.0</td>
<td>FRED</td>
<td>?</td>
<td>Strong</td>
</tr>
<tr>
<td>GX 339−4</td>
<td>No$^c$</td>
<td>8.7–9.3</td>
<td>Episodic</td>
<td>Strong$^e$</td>
<td>Weak</td>
</tr>
<tr>
<td>GRS 1716−249</td>
<td>No$^e$</td>
<td>2.3–11.2</td>
<td>Episodic</td>
<td>Strong$^f$</td>
<td>Strong</td>
</tr>
<tr>
<td>Power-Law Gamma-Ray State</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GRS 1009−45</td>
<td>Yes$^h$</td>
<td>$\simeq 3.9$</td>
<td>FRED</td>
<td>Weak$^f$</td>
<td>UL</td>
</tr>
<tr>
<td>4U 1543−47</td>
<td>Yes$^i$</td>
<td>0.5–1.7</td>
<td>FRED</td>
<td>?</td>
<td>UL</td>
</tr>
<tr>
<td>GRO J1655−40</td>
<td>Yes$^j$</td>
<td>5.1–9.5</td>
<td>Episodic</td>
<td>Moderate$^k$</td>
<td>UL</td>
</tr>
<tr>
<td>GRS 1716−249</td>
<td>?</td>
<td>0.6–1.7</td>
<td>Episodic</td>
<td>?</td>
<td>UL</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>Yes$^m$</td>
<td>27–45</td>
<td>Episodic</td>
<td>Moderate$^k$</td>
<td>UL</td>
</tr>
</tbody>
</table>

**Note**—“FRED” denotes a fast rise and exponential decay light curve. Question marks indicate no reports in the literature. “UL” indicates no evidence at the sensitivity of the OSSE observations; only an upper limit is available. “SL jet” indicates apparent superluminal radio jet.