The linguistics of LISA sources

• Overview: key LISA sources.
  – What do we hope to learn from these sources?
  – What is the character of the signals they generate?

• How do we design a strategy to measure them?
  – Big difference between “detection” and “measurement”!
  – Can we exploit commonalities with other analysis techniques?
  – Can we combine GW information with other channels to maximize the astrophysical payoff?
Contrast: LISA sources vs LIGO

- **LIGO:**
  - High frequency
  - Many interesting sources are rare, short lived
- **Typically listening for soloists.**

- **LISA:**
  - Low frequency
  - Many interesting sources are common, long lived.

- **Typically trying to pick a voice out of a chorus.**
Source confusion, part 1
Source confusion, part 2
“What kind of information do you need for data analysis?”

Speaking generally: we have no clue!

Need to understand the linguistics of our sources better: *any* robust distinguishing characteristic is useful.

Ear + brain makes a pretty decent spectral analysis/pattern recognition system!
Source Tour: galactic binaries

- Thousands or millions of sources
- “On” all the time
- Essentially monochromatic
Source Tour: massive BBH

- Rate uncertain: could be high or low
- Each event lasts weeks to years
- Sweeps through a broad frequency band
Source Tour: extreme mass ratio insp.

- Rate rather uncertain: could be many “on” at once
- Each event lasts months to years
- Sweeps through a relatively narrow frequency band
These sources are “on” at the same time!

This is not necessarily a problem: each source has a unique “sound” and in principle should be distinguishable within the chorus.

Strong need to understand the character of each voice well enough that we can do this in practice, and need to develop the techniques for actually distinguishing them.
Gravitational-wave linguistics

Understanding what the source is saying well enough that we can robustly detect it, separate it from the rest of the voices, and learn what it says about its source.

Waveforms are useful and important tools but they are far from the full story!

In particular, getting the waveform “right” in all its gory detail is rarely needed.
Galactic binary measurement & science

- Intrinsically monochromatic (or nearly so)
  - \( \frac{df}{dt} \) probably dominated by GW emission:

\[
\frac{df}{dt} = 10^{-10} \text{ Hz/year} \left( \frac{Mc}{0.7 \text{ M}_\odot} \right)^{5/3} \left( \frac{f}{0.001 \text{ Hz}} \right)^{11/3}
\]

- Not going to see any frequency change at low frequencies, low masses.
- Second derivative, if visible, may include more complicated physics: tidal heating, mass transfer, as well as GW emission.

- Strong modulation by detector motion!
GBM & S, part II

- Huge population density in frequency space:
  \[
  \frac{dN}{df} = 2 \times 10^8 \text{ Hz}^{-1} \left( \frac{0.001 \text{ Hz}}{f} \right)^{11/3}
  \]

- Fit by Phinney to calculations by Webbink and Han
  - Typical frequency bin width: \( \delta f \approx 10^{-7} \text{ Hz} \)

- Punchline: have many binaries per bin at low frequencies, few per bin at high frequencies.

- Transition from confused background to series of non-confused lines at \( f \approx 2 - 3 \times 10^{-3} \text{ Hz} \)
• Monochromatic binaries:
  
  - All we can get *in principle* from these sources are the two polarization amplitudes, frequency, and position: lack of frequency evolution means masses and distance are degenerate. *This is still a LOT of information!*
  
  - For example, with position we can search for EM counterpart. In EM measurement, masses and inclination are degenerate. Ratio of GW polarization amplitudes provides inclination. *EM + GW combined teaches us a LOT more about the system!*
  
  - Also a lot of population information in confused background: sets numbers, perhaps tells distribution.
GBM & S, part IV

- Some monochromatic emitters are already known: positions known in advance, periods known in advance.
  - Definite calibrators: if we don't measure the waves from these guys, we're in trouble! Either Einstein's wrong or LISA's broken...
  - Measurement presents science opportunities as well. New/independent measures of inclinations and masses of these sources.
GBM & S, part V

• Chirping binaries:
  - As we move to higher frequencies, the chances of measuring $f_{\dot{\nu}}$ and $f_{\ddot{\nu}}$ gets stronger. However, the number of sources should get smaller.
  - $f_{\dot{\nu}}$ alone: gives us the chirp mass of the system. Can now begin breaking degeneracies!
  - $f_{\ddot{\nu}}$: probably only distinguishible for highest masses and/or highest frequencies. Physics beyond GW emission? Possibility of tidal heating or mass transfer; big dependence on stellar structure (eg, binaries of CO white dwarfs vs He dwarfs).
Revisit LISA sensitivity:
Massive binary black holes

- Waves identical for LISA and for LIGO, modulo mass scaling!

- Biggest difference is in the astrophysics: source of events extremely different in these cases.
  - “Local”: binaries formed following mergers of galaxies at relatively low redshift ($z \sim 1$ish)
  - “Distant”: binaries formed following mergers of the building blocks of “mature” galaxies ($z > 2 – 5$ish).

- Different astrophysics means measurable epochs very different: lots of inspiral measurable for LISA.
MBBH wave character

• Formation mechanism likely to impose interesting parameter selections on measured binaries:
  – Form by fairly random captures: aligned spins extremely unlikely.
  – Mass ratio likely to be significant: wide variety of black hole masses seen in galaxies.

• Suggests that the Flanagan & Hughes merger power estimates are probably irrelevant!
  – Rather than a long and loud merger driven by shedding of angular momentum, there may be a relatively quick transition from inspiral to ringdown.
MBBH wave character, part II

• Extremely strong inspirals! SNR (assuming coherent phase up to the ISCO) is often in the range of hundreds.
  - Even if we can't get all the way into the ISCO with our modeled waveforms, we can do a very solid detection: might lose several tens of percent of SNR by not getting “all” of the inspiral, but that's OK.
  - Signal strength in those last several (dozen?) orbits is particularly strong.

• Current understanding good enough???
MBBH mergers in nature? NGC 326

http://www.ira.bo.cnr.it/~murgia

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Rate issues

- Are mergers efficient - is the rate of MBBH mergers comparable to the rate of galaxy mergers? If so, we should have something like 1 major merger per year out to $z \sim 5$ish (Merritt & Ekers 2002).

- What about not so major mergers? Beyond $z \sim 5$?

- A lot of uncertainty! Menou, Haiman, & Narayanan (2001) showed that very different primordial seeding of dark matter halos at large $z$ leads to essentially identical black hole mass distributions in the present.

- Also issue of mass distribution! LISA is optimal for redshifted masses around $10^5 - 10^6$ $M_{sun}$; still OK for smaller masses, fairly poor for larger masses.
MBBH Science

• LISA will be sensing these events to enormous distances: new tools for cosmology.

• Measurement gives redshifted masses, sky position, and distance to source; cosmography allows us to infer redshift from distance. Learn about black hole masses as a function of redshift.
  – Direct probe of structure forming processes.
  – Also gives a census of black hole demographics in the (relatively) early universe.
MBBH Science, part II

• Spins?
  – Spin impacts both phase and amplitude of waves.
  – Modulation is most effective in the last, strongest orbits. Should be easier to detangle than for LIGO.

• EM Counterparts?
  – Not clear they exist or are easily measurable!
  – Give sky position much better than the GWs alone can do – improves all other parameter accuracies.
  – Could provide redshift independently! Break \((M,z)\) degeneracy. Extremely precise standard candle.
Extreme mass ratio inspiral (EMRI)

- One of the more interesting “relativity” sources: opens possibility of “mapping” black hole spacetimes.
- Also relatively easy to model waveforms: extreme mass ratio means perturbative approach is fine.
- Prescription for very rigorous radiation reaction (Mino, Sasaki, Tanaka 1997; Quinn & Wald 1997) has been specified. Lots of current work to develop an implementation.
- *Do we really need such rigorous waveforms?*
EMRI astrophysics

- The smaller member of the binary must be compact – preferably a neutron star or black hole.
  - White dwarf is OK, but can introduce complications.
- Rates are more or less all over the map!
  - Sigurdsson examined all the calculations for compact body capture (LISA symposium talk, summer 2002).
  - All calculations are essentially consistent, but make different assumptions (all of which are reasonable, and may reflect conditions in different galaxies).
- Punchline: we can reasonably expect at least “some” events per year, perhaps hundreds.
EMRI relativity

- Black hole spacetimes determined by a unique family of multipole moments:
  \[ M_l + i S_l = M (i a)^l \]

- Orbits have 3 characteristic frequencies:
  \[ \Omega_\phi \text{ : associated with motion around spin axis} \]
  \[ \Omega_\theta \text{ : associated with latitudinal motion} \]
  \[ \Omega_r \text{ : associated with radial motion} \]
Mapping

- Consider Newtonian limit: for spherical mass,
  \[ V(r) = -\frac{GM}{r} \]
- Frequencies equal: \( \theta \) and \( \phi \) by spherical symmetry, \( r \) by Bertrand's theorem.
- Add a quadrupolar distortion:
  \[ V(r) = -\frac{GM}{r} + \frac{Q Y_{20}(\theta)}{r^3} \]
- Measure frequencies, measure \( Q \).
- Do this for the earth: geodesy.
- For black holes: bothrodesy. (Or “holiodesy”.)
How do we describe the signal?

• Tri-periodic gravitational waves: the orbital frequencies separately evolve and influence waves.

• *How well do we need to know frequency evolution?* Are effects second-order in mass ratio important?
  
  – Several things affect the inspiral at this level:
    
    • Spin of the small body
    
    • Second order self forces
    
    • Accretion induced drag
  
  – We can never robustly detangle all of these effects

• Need measurement scheme insensitive to “small” second order stuff.

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How do we measure robustly?

- Think about the form of the signal: three main frequencies dominate the dynamics. Can we find a way to coherently track these in a way that isn't sensitive to small scale details?
  
  - Intuition from circular orbits: wave appears to be decomposable as a multi-voice chirp:

    \[ h(t) = \sum H_{lmk}(t) \exp\left[i \psi_{lmk}(t)\right] \]

    - \( H(t) \) evolves very slowly, \( \Psi(t) \) varies (relatively) quickly.
    - Quite likely this form doesn't work well for eccentric orbits: need to ascertain how large \( e \) is OK.

- Can we search robustly for this kind of variation?
Circular multivoice structure

- Example taken from Hughes (2001). Shows phase & amplitude functions for hole with $a = 0.36 \, M$. Harmonic indices $l$ and $m$ are fixed to 2; the index $k$ ($\theta$ frequency) varies.

- “Effective $h$” taken from Finn & Thorne (2000). Note that a lot of the SNR accumulates early on! Really want phase coherence in early bits.

- Structure holds independent of spin.
Is this useful?

- Early part of the signal – where a large fraction of the SNR accumulates – shows most important phase functions evolving very slowly.
- Intuition from coalescing binaries may mislead! More between binaries and pulsars (r-modes?)
- Better off (for detection purposes) *throwing away as much physics as possible* and just trying to phase lock to the varying sinusoids. Perhaps just need a few *fs* and *fdots*? Fast chirp transform?
Eccentricity

- What keeps me up at night: robust detection with eccentricity.

- Multivoice may be fine for circ, lousy for ecc. Is that OK? Can we find a separate approach for ecc?
Wrap up

• Mantra: “Robustness”. We cannot rely on techniques that are hyper-sensitive to small effects.

• Especially for detection, strive to capture the feel of the waveform space rather than getting all details right: better to be conversant in the language than to have tried to map out the dictionary beforehand!