Multi-Waveform Search Method for Intermediate Duration Gravitational Waves Using the Cross Correlation Algorithm (CoCoA):

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Abstract

Gamma Ray Bursts (GRBs) are flashes of gamma-rays thought to originate from rare forms of massive star collapse (long GRBs) or from mergers of compact binaries (short GRBs) containing at least one neutron star (NS). The nature of the post-explosion/post-merger remnant (NS versus black hole, BH) remains highly debated. In ~10% of GRBs the temporal evolution of the X-Ray afterglow follows the flash of gamma-rays is observed to ‘plateau’ on timescales of $10^2$ to $10^4$ seconds since explosion. It has been suggested that this plateau feature may signal the presence of energy injection from a long-lived, highly magnetized NS (magnetar.) The Cross-Correlation Algorithm (CoCoA) aims to optimize searches for intermediate duration ($10^2$ to $10^4$ second) gravitational waves (GWs). In this work, we further develop the detection statistics on which CoCoA is based to allow multi-waveform searches that can span a physically-motivated parameter space, thus accounting for uncertainties in the physical properties of post-GRB remnants.

Unexplained Plateau in GRB X-Ray Emission

- Light curves found by E-M observations of Gamma Ray Burst afterglow have some features that differ from those predicted by the standard GRB model including a plateau in the X-ray afterglow.
- We theorize that the x-ray plateau is caused by a highly magnetized Neutron Star (magnetar) acting as the central engine rather than a Black Hole (for at least a brief period of time.)
- These magnetars may emit Gravitational waves on a timescale similar to that of an x-ray plateau, a timescale largely unexplored by LIGO searches.

Cross Correlation Algorithm (CoCoA)

- CoCoA based on Short-time Fourier Transform (SFT).
- Stretch of time-domain detector data broken up into several segments of duration $\Delta T_{\text{filt}}$ (baseline).
- Discrete Fourier transform taken of each baseline segment, then arranged into time-frequency map to track evolution of the signal.
- Detection statistic ($\mathcal{H}$) built by cross-correlating pairs of SFTs: bins containing signal correlate (after sliding), resulting in an “excess” in detection statistic compared to uncorrelated bkg noise.

Different Ways to Correlate

- Stochastic limit: Only pairs from the same timeframe from different detector are correlated, $\rho$ distributed as a Gaussian with zero mean for bkg only (non-zero mean if signal present).
- Fully coherent limit: All possible pairs are correlated, $\rho$ distributed as $\chi^2$ with 2 d.o.f.; non-central $\chi^2$ if signal present.

Testing on Real Data

- Previously CoCoA used simulated white data, an average approximation of LIGO data over a given frequency range.
- To ensure the method works on real data we compare three methods, real data from S6, simulated white assuming S6 sensitivity and colored noise which simulates the PSD of real noise without any strong lines.
- To test we compare the ratio of scaling factors between calculated and recovered for each of the three types of data.
- We find no discrepancy in scaling factors of more than 10% other than in a semi-coherent search which uses a flat PSD assumption that is not true with colored or real data.

Searching for Many Waveforms

- For a typical search we use the initial parameters of the magnetar, the start time of GW emission and the cause of GW emission may be unknown.
- We perform a real search, a waveform bank covering a realistic parameter space is necessary where each waveform is searched for all possible starting times. Searching for many templates increases likelihood that a false alarm will occur (trial factor).
- We implement a multi-trial search with CoCoA via the “maximum normalized p statistic” for the combined set of waveforms.

Background

- In order to quantify a detection we build a background distribution by performing a full search several times through the data at times near that of the target, but not at any time a signal may exist.
- Next we select an allowed probability of finding a false alarm for a given search, known as the false alarm probability (FAP).
- The value of the detection statistic where the background probability distribution crosses the FAP is set as the FAP threshold. All detections above this threshold are candidates for further study.

Upper Limits

- We find Upper Limits by injecting a waveform from the waveform bank into the background data at many distances directly between two starting times that are searched for.
- The ratio of relevant detections at a given distance is called the efficiency. For each distance injection the efficiency is plotted vs. the distance and fit to a sigmoid curve. Where the sigmoid curve crosses a chosen allowed efficiency is the upper limit distance (in Mpc)

Conclusions

- Plateaus in the X-Ray afterglow from GRB afterglow may be caused by magnetars.
- Magnetars undergoing extreme conditions are prime candidates for GW detection.
- CoCoA attempts to provide a method to detect GWs with durations of $10^2$ - $10^4$ seconds.
- CoCoA has been updated to use real data from the LIGO detectors.
- Uncertainty in the start time and physical parameters of the GW emission are now accounted for by CoCoA.
- In future work we plan to create a full parameter space for at least one model of waveform.