Galactic Magnetars and Cosmic Explorer

SUMMARY

Next-generation (XG) gravitational-wave observatories like Cosmic Explorer will have greatly improved sensitivity at frequencies in the 1 to 3 kHz range compared to current generation detectors. This improved high-frequency sensitivity could open up new gravitational-wave sources to observe. Isolated neutron stars with exceptionally strong magnetic fields, called magnetars (Duncan and Thompson 1992), are hypothesized to produce gravitational-wave signals driven by internal oscillations referred to as "f-modes" (Thompson and Duncan 1995; de Freitas Pacheco 1998) in the 1 to 3 kHz regime. Targeted searches have been performed in LIGO-Virgo data in previous observing runs with no detections (B. P. Abbott et al. 2019; R. Abbott, Abe, Acernese, et al. 2022; R. Abbott, T. D. Abbott, et al. 2022). The improved sensitivity of XG observatories may allow us to measure this never-before-seen type of signal and shed new light on these mysterious objects.

Key question(s) and scientific context in brief

The improved high-frequency sensitivity of XG gravitational-wave (GW) observatories will allow searches for GWs associated with magnetar f-modes to provide important astrophysical insights, including the neutron star equation of state (EoS), either from detections or from meaningful limits. We present modeling which suggests that targeted searches with XG detectors like Cosmic Explorer can make the astrophysics of magnetars accessible.

Potential scientific impact of XG detectors on the key questions

The simplest description of an f-mode is that of a damped sinusoid, following the logic of Echeverria 1989 and Finn 1992. By describing the amplitude, frequency, and damping time terms with EoS-independent fitting functions described by Lasky, Zink, and Kokkotas 2012 and Andersson and Kokkotas 1998, we can construct a rudimentary model for the gravitational wave emission for such an oscillation. Estimates place the damping times of these modes at less than 1 second (Levin 2006). Using astrophysically-motivated source parameters, such as mass, radius, and magnetic field strength, we can estimate the strength of potential signals for various detector sensitivities. This simple model predicts that for a magnetar with a magnetic field strength consistent with giant flare measurements, we could potentially expect detections from anywhere in the galaxy using an XG detector like Cosmic Explorer. Assuming that the more frequent (several per year) ordinary X-ray flares also can ring-up f-modes, likely with smaller amplitudes, a nearby (few kpc) magnetar may provide a similarly appealing target. Figure 1 shows the substantial improvement to the sensitive distance that XG detectors provide over current-generation detectors when assuming a magnetic field strength of $\sim 10^{16}$ Gauss, a value predicted by Stella et al. 2005 and Mereghetti 2008 for giant flares like the 2004 giant flare from SGR 1806-20.

Benchmarks for XG detectors to enable the scientific impact

This analysis benefits most from improved strain sensitivity in the 1 to 3 kHz region. The Cosmic Explorer curve in Figure 1 was estimated using a characteristic sensitivity in this region of 5×10^{-25} to 2×10^{-24} $\mathrm{Hz}^{-1/2}$ (computed by Srivastava et al. 2022).

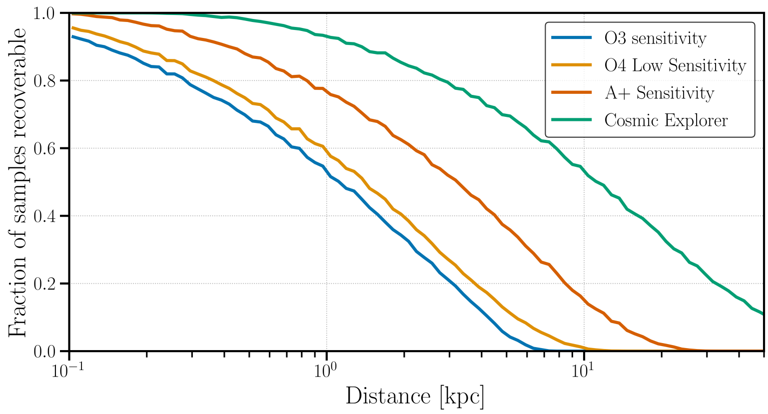

Figure 1: Sensitive ranges of current and future detectors to gravitational wave emission from a magnetar f-mode assuming a magnetic field similar to a magnetar giant flare. Detection statistic is represented as the fraction of random samples in a distance bin with a signal-to-noise ratio greater than 1. Samples were drawn from astrophysically motivated mass and radius ranges (1 - 2.5 M_{sun} and 8 - 16 km) and assuming a magnetic field strength of 1×10^{16} G. Cosmic Explorer provides sensitivity to GWs associated with giant flares for the entire galaxy.

SCIENTIFIC IMPACT OF XG DETECTORS

- Potential first direct detection of f-modes associated with magnetars
- Improved understanding of X-ray emission mechanisms in magnetars
- Constraints on magnetar/neutron star Equation of State

Dependencies on other multi-messenger capabilities

The magnetar f-modes are hypothesized to be associated with X-ray flares. Hence, the targeted searches proposed here rely on external detectors. Currently, these are primarily provided by FERMI GBM, SWIFT BAT, and the IPN. The capacity of external groups to determine the distance to a source is also essential.

XG DETECTOR AND NETWORK REQUIREMENTS

No special network requirements.

Authors

Matthew Ball, University of Oregon, LIGO Scientific Collaboration, mball2@uoregon.edu
Raymond Frey, University of Oregon, rayfrey@uoregon.edu

Bibliography

[1] B. P. Abbott et al. “Search for Transient Gravitational-wave Signals Associated with Magnetar Bursts during Advanced LIGO’s Second Observing Run”. In: *The Astrophysical Journal* 874.2 (Apr. 2019), p. 163. DOI: 10.3847/1538-4357/ab0e15. URL: https://dx.doi.org/10.3847/1538-4357/ab0e15.

[2] R. Abbott, T. D. Abbott, et al. *Search for Gravitational Waves Associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO–Virgo Observing Run O3a*. 2022. arXiv: 2203.12038 [astro-ph.HE].

[3] R. Abbott, H. Abe, F. Acernese, et al. “Search for gravitational-wave transients associated with magnetar bursts in Advanced LIGO and Advanced Virgo data from the third observing run”. In: *arXiv e-prints*, arXiv:2210.10931 (2022), arXiv:2210.10931. arXiv: 2210.10931 [astro-ph.HE].

[4] Nils Andersson and Kostas D. Kokkotas. “Towards gravitational wave asteroseismology”. In: *Monthly Notices of the Royal Astronomical Society* 299.4 (Oct. 1998), pp. 1059–1068. ISSN: 0035-8711. DOI: 10.1046/j.1365-8711.1998.01840.x. eprint: https://academic.oup.com/mnras/article-pdf/299/4/1059/3869494/299-4-1059.pdf. URL: https://doi.org/10.1046/j.1365-8711.1998.01840.x.

[5] J. A. de Freitas Pacheco. “Do soft gamma repeaters emit gravitational waves?” In: *Astronomy and Astrophysics* 336 (Aug. 1998), pp. 397–401. DOI: 10.48550/arXiv.astro-ph/9805321. arXiv: astro-ph/9805321 [astro-ph].

[6] Robert C. Duncan and Christopher Thompson. “Formation of Very Strongly Magnetized Neutron Stars: Implications for Gamma-Ray Bursts”. In: *Astrophysical Journal, Letters* 392 (June 1992), p. L9. DOI: 10.1086/186413.

[7] Fernando Echeverria. “Gravitational-wave measurements of the mass and angular momentum of a black hole”. In: *Phys. Rev. D* 40 (10 Nov. 1989), pp. 3194–3203. DOI: 10.1103/PhysRevD.40.3194. URL: https://link.aps.org/doi/10.1103/PhysRevD.40.3194.

[8] Lee S. Finn. “Detection, measurement, and gravitational radiation”. In: *Phys. Rev. D* 46 (12 Dec. 1992), pp. 5236–5249. DOI: 10.1103/PhysRevD.46.5236. URL: https://link.aps.org/doi/10.1103/PhysRevD.46.5236.

[9] Paul D. Lasky, Burkhard Zink, and Kostas D. Kokkotas. “Gravitational Waves and Hydromagnetic Instabilities in Rotating Magnetized Neutron Stars”. In: *arXiv e-prints*, arXiv:1203.3590 (2012), arXiv:1203.3590. arXiv: 1203.3590 [astro-ph.SR].

[10] Yuri Levin. “QPOs during magnetar flares are not driven by mechanical normal modes of the crust”. In: *Monthly Notices of the Royal Astronomical Society: Letters* 368.1 (May 2006), pp. L35–L38. ISSN: 1745-3925. DOI: 10.1111/j.1745-3933.2006.00155.x. eprint: https://academic.oup.com/mnrasl/article-pdf/368/1/L35/2831330/368-1-L35.pdf. URL: https://doi.org/10.1111/j.1745-3933.2006.00155.x.

[11] Sandro Mereghetti. “The strongest cosmic magnets: soft gamma-ray repeaters and anomalous X-ray pulsars”. In: *The Astronomy and Astrophysics Review* 15.4 (July 2008), pp. 225–287. ISSN: 1432-0754. DOI: 10.1007/s00159-008-0011-z. URL: https://doi.org/10.1007/s00159-008-0011-z.

[12] Varun Srivastava et al. "Science-driven Tunable Design of Cosmic Explorer Detectors". In: *The Astrophysical Journal* 931.1 (May 2022), p. 22. DOI: 10.3847/1538-4357/ac5f04. URL: https://doi.org/10.3847/1538-4357/ac5f04.

[13] L. Stella et al. "Gravitational Radiation from Newborn Magnetars in the Virgo Cluster". In: *The Astrophysical Journal* 634.2 (Nov. 2005), p. L165. DOI: 10.1086/498685. URL: https://dx.doi.org/10.1086/498685.

[14] Christopher Thompson and Robert C. Duncan. "The soft gamma repeaters as very strongly magnetized neutron stars - I. Radiative mechanism for outbursts". In: *Monthly Notices of the Royal Astronomical Society* 275.2 (July 1995), pp. 255–300. DOI: 10.1093/mnras/275.2.255.