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B. Abbott,[16] R. Abbott,[16] R. Adhikari,[16] P. Ajith,[2] B. Allen,[2,54] G. Allen,[32] R. Amin,[20] S. B. Anderson,[16] W. G. Anderson,[54] M. A. Arain,[41] M. Araya,[16] H. Armandula,[16] P. Armor,[54] Y. Aso,[10] S. Aston,[40] P. Aufmuth,[15] C. Aulbert,[2] S. Babak,[1] S. Ballmer,[16] H. Bantilan,[8] B. C. Barish,[16] C. Barker,[18] D. Barker,[18] B. Barr,[42] P. Barriga,[53] M. A. Barton,[42] I. Bartos,[10] M. Bastarrika,[42] K. Bayer,[17] J. Betzwieser,[16] P. T. Beyersdorf,[28] I. A. Bilenko,[23] G. Billingsley,[16] R. Biswas,[54] E. Black,[16] K. Blackburn,[16] L. Blackburn,[17] D. Blair,[53] B. Bland,[18] T. P. Bodiya,[17] L. Bogue,[19] R. Bork,[16] V. Boschi,[16] S. Bose,[55] P. R. Brady,[54] V. B. Braginsky,[23] J. E. Brau,[47] M. Brinkmann,[2] A. Brooks,[16] D. A. Brown,[33] G. Brunet,[17] A. Bullington,[32] A. Buonanno,[43] O. Burmeister,[2] R. L. Byer,[32] L. Cadonati,[44] G. Cagnoli,[42] J. B. Camp,[24] J. Cannizzo,[24] K. Cannon,[16] J. Cao,[17] L. Cardenas,[16] T. Casebolt,[32] G. Castaldi,[50] C. Cepeda,[16] E. Chalkley,[42] P. Charlton,[9] S. Chatterji,[16] S. Chelkowski,[40] Y. Chen,[6,1] N. Christensen,[8] D. Clark,[32] J. Clark,[42] T. Cokelaer,[7] R. Conte,[49] D. Cook,[18] T. Corbitt,[17] D. Coyne,[16] J. D. E. Creighton,[54] A. Cumming,[42] L. Cunningham,[42] R. M. Cutler,[40] J. Dalrymple,[33] K. Danzmann,[15,2] G. Davies,[7] D. DeBra,[32] J. Degallaix,[1] M. Degree,[32] V. Dergachev,[45] S. Desai,[34] R. DeSalvo,[16] S. Dhurandhar,[14] M. Díaz,[36] J. Dickson,[4] A. Dietz,[7] F. Donovan,[17] K. L. Dooley,[41] E. E. Doomes,[31] R. W. P. Drever,[5] I. Duke,[17] J.-C. Dumas,[53] R. J. Dupuis,[16] J. G. Dwyer,[10] C. Echols,[16] A. Effler,[18] P. Ehrens,[16] E. Espinoza,[16] T. Etzel,[16] T. Evans,[19] S. Fairhurst,[7] Y. Fan,[53] D. Fazi,[16] H. Fehrmann,[2] M. M. Fejer,[32] L. S. Finn,[34] K. Flasch,[54] N. Fotopoulos,[54] A. Freise,[40] R. Frey,[47] T. Fricke,[16,48] P. Fritschel,[17] V. V. Frolov,[19] M. Fyffe,[19] J. Garofoli,[18] I. Gholami,[1] J. A. Giaime,[19,20] S. Giampanis,[48] K. D. Giardina,[19] K. Goda,[17] E. Goetz,[45] L. Goggin,[16] G. González,[20] S. Gossler,[2] R. Gouaty,[20] A. Grant,[42] S. Gras,[53] C. Gray,[18] M. Gray,[4] R. J. S. Greenhalgh,[27] A. M. Gretarsson,[11] F. Grimaldi,[17] R. Grosso,[36] H. Grote,[2] S. Grunewald,[1] M. Guenther,[18] E. K. Gustafson,[16] R. Gustafson,[45] B. Hage,[15] J. M. Hallam,[40] D. Hammer,[54] C. Hanna,[20] J. Hanson,[19] J. Harms,[2] G. Harry,[17] E. Harstad,[47] K. Hayama,[36] T. Hayler,[27] J. Heefner,[16] I. S. Heng,[42] M. Hennessy,[32] A. Heptonstall,[42] M. Hewitson,[2] S. Hild,[40] E. Hirose,[33] D. Hoak,[19] D. Hosken,[39] J. Hough,[42] S. H. Huttner,[42] D. Ingram,[18] M. Ito,[47] A. Ivanov,[16] B. Johnson,[18] W. W. Johnson,[20] D. I. Jones,[51] G. Jones,[7] R. Jones,[42] L. Ju,[53] P. Kalmus,[10] V. Kalogera,[26] S. Kamat,[10] J. Kanner,[43] D. Kasprzyk,[40] E. Katsavounidis,[17] K. Kawabe,[18] S. Kawamura,[25] F. Kawazoe,[25] W. Kells,[16] D. G. Keppel,[16] F. Ya. Khalili,[23] R. Khan,[10] E. Khazanov,[13] C. Kim,[26] P. King,[16] J. S. Kissel,[20] S. Klimenko,[41] K. Kokeyama,[25] V. Kondrashov,[16] R. K. Kopparapu,[34] D. Kozak,[16] I. Kozhevatov,[13] B. Krishnan,[1] P. Kwee,[15] P. K. Lam,[4] M. Landry,[18] M. M. Lang,[34] B. Lantz,[32] A. Lazzarini,[16] M. Lei,[16] N. Leindecker,[32] V. Leonhardt,[25] I. Leonor,[47] K. Libbrecht,[16] H. Lin,[41] P. Lindquist,[16] N. A. Lockerbie,[52] D. Lodhia,[40] M. Lormand,[19] P. Lu,[32] M. Lubinski,[18] A. Lucianetti,[41] H. Lück,[15,2] B. Machenschalk,[2] M. MacInnis,[17] M. Mageswaran,[16] K. Mailand,[16] V. Mandic,[46] S. Márka,[10] Z. Márka,[10] A. Markosyan,[32] J. Markowitz,[17] E. Maros,[16] I. Martin,[42] R. M. Martin,[41] J. N. Marx,[16] K. Mason,[17] F. Matichard,[20] L. Matone,[10] R. Matzner,[35] N. Mavalvala,[17] R. McCarthy,[18] D. E. McClelland,[4] S. C. McGuire,[31] M. McHugh,[22] G. McIntyre,[16] G. McIvor,[35] D. McKechan,[7] K. McKenzie,[4] T. Meier,[15] A. Melissinos,[48] G. Mendell,[18] R. A. Mercer,[41] S. Meshkov,[16] C. J. Messenger,[2] D. Meyers,[16] J. Miller,[42,16] J. Minelli,[34] S. Mitra,[14] V. P. Mitrofanov,[23] G. Mitselmakher,[41] R. Mittleman,[17] O. Miyakawa,[16] B. Moe,[54] S. Mohanty,[36] G. Moreno,[18] K. Mossavi,[2] C. MowLowry,[4] G. Mueller,[41] S. Mukherjee,[36] H. Mukhopadhyay,[14] H. Müller-Ebhardt,[2] J. Munch,[39] P. Murray,[42] E. Myers,[18] J. Myers,[18] T. Nash,[16] J. Nelson,[42] G. Newton,[42] A. Nishizawa,[25] K. Numata,[24] J. O'Dell,[27] G. Ogin,[16] B. O'Reilly,[19] R. O'Shaughnessy,[34] D. J. Ottaway,[17] R. S. Ottens,[41] H. Overmier,[19] B. J. Owen,[34] Y. Pan,[43] C. Pankow,[41] M. A. Papa,[1,54] V. Parameshwaraiah,[18] P. Patel,[16] M. Pedraza,[16] S. Penn,[12] A. Perreca,[40] T. Petrie,[34] I. M. Pinto,[50] M. Pitkin,[42] H. J. Pletsch,[2] M. V. Plissi,[42] F. Postiglione,[49] M. Principe,[50] R. Prix,[2] V. Quetschke,[41] F. Raab,[18] D. S. Rabeling,[4] H. Radkins,[18] N. Rainer,[2] M. Rakhmanov,[30] M. Ramsunder,[34] H. Rehbein,[2] S. Reid,[42] D. H. Reitze,[41] R. Riesen,[19] K. Riles,[45] B. Rivera,[18] N. A. Robertson,[16,42] C. Robinson,[7] E. L. Robinson,[40] S. Roddy,[19] A. Rodriguez,[20] A. M. Rogan,[55] J. Rollins,[10] J. D. Romano,[36] J. Romie,[19] R. Route,[32] S. Rowan,[42] A. Rüdiger,[2] L. Ruet,[17] P. Russell,[16] K. Ryan,[18] S. Sakata,[25] M. Samidi,[16] L. Sancho de la Jordana,[38] V. Sandberg,[18] V. Sannibale,[16] S. Saraf,[29] P. Sarin,[17] B. S. Sathyaprakash,[7] S. Sato,[25] P. R. Saulson,[33] R. Savage,[18] P. Savov,[6] S. W. Schediwy,[53] R. Schilling,[2] R. Schnabel,[2] R. Schofield,[47] B. F. Schutz,[1,7] P. Schwinberg,[18] S. M. Scott,[4] A. C. Searle,[4] B. Sears,[16] F. Seifert,[2] D. Sellers,[19] A. S. Sengupta,[16] P. Shawhan,[43] D. H. Shoemaker,[17] A. Sibley,[19] X. Siemens,[54] D. Sigg,[18] S. Sinha,[32] A. M. Sintes,[38,1] B. J. J. Slagmolen,[4] J. Slutsky,[20] J. R. Smith,[33] M. R. Smith,[16] N. D. Smith,[17] K. Somiya,[2,1] B. Sorazu,[42] L. C. Stein,[17] A. Stochino,[16] R. Stone,[36] K. A. Strain,[42] D. M. Strom,[47] A. Stuver,[19] T. Z. Summerscales,[3] K.-X. Sun,[32] M. Sung,[20] P. J. Sutton,[7] H. Takahashi,[1] D. B. Tanner,[41] R. Taylor,[16] R. Taylor,[42] J. Thacker,[19] K. A. Thorne,[34] K. S. Thorne,[6] A. Thüring,[15] K. V. Tokmakov,[42] C. Torres,[19] C. Torrie,[42] G. Traylor,[19] M. Trias,[38] W. Tyler,[16] D. Ugolini,[37] J. Ulmen,[32]

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K. Urbanek,[32] H. Vahlbruch,[15] C. Van Den Broeck,[7] M. van der Sluys,[26] S. Vass,[16] R. Vaulin,[54] A. Vecchio,[40] J. Veitch,[40] P. Veitch,[39] A. Villar,[16] C. Vorvick,[18] S. P. Vyachanin,[23] S. J. Waldman,[16] L. Wallace,[16] H. Ward,[42] R. Ward,[16] M. Weinert,[2] A. Weinstein,[16] R. Weiss,[17] S. Wen,[20] K. Wette,[4] J. T. Whelan,[1] S. E. Whitcomb,[16] B. F. Whiting,[41] C. Wilkinson,[18] P. A. Willems,[16] H. R. Williams,[34] L. Williams,[41] B. Willke,[15,2] I. Wilmut,[27] W. Winkler,[2] C. C. Wipf,[17] A. G. Wiseman,[54] G. Woan,[42] R. Wooley,[19] J. Worden,[18] W. Wu,[41] I. Yakushin,[19] H. Yamamoto,[16] Z. Yan,[53] S. Yoshida,[30] M. Zanolin,[11] J. Zhang,[45] L. Zhang,[16] C. Zhao,[53] N. Zotov,[21] M. Zucker,[17] and J. Zweizig[16]

(LIGO Scientific Collaboration)

[1]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Golm, Germany*
[2]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[3]*Andrews University, Berrien Springs, Michigan 49104, USA*
[4]*Australian National University, Canberra, 0200, Australia*
[5]*California Institute of Technology, Pasadena, California 91125, USA*
[6]*Caltech-CaRT, Pasadena, California 91125, USA*
[7]*Cardiff University, Cardiff, CF24 3AA, United Kingdom*
[8]*Carleton College, Northfield, Minnesota 55057, USA*
[9]*Charles Sturt University, Wagga Wagga, NSW 2678, Australia*
[10]*Columbia University, New York, New York 10027, USA*
[11]*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
[12]*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
[13]*Institute of Applied Physics, Nizhny Novgorod, 603950, Russia*
[14]*Inter-University Center for Astronomy and Astrophysics, Pune - 411007, India*
[15]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[16]*LIGO-California Institute of Technology, Pasadena, California 91125, USA*
[17]*LIGO-Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[18]*LIGO Hanford Observatory, Richland, Washington 99352, USA*
[19]*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
[20]*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[21]*Louisiana Tech University, Ruston, Louisiana 71272, USA*
[22]*Loyola University, New Orleans, Louisiana 70118, USA*
[23]*Moscow State University, Moscow, 119992, Russia*
[24]*NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
[25]*National Astronomical Observatory of Japan, Tokyo 181-8588, Japan*
[26]*Northwestern University, Evanston, Illinois 60208, USA*
[27]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[28]*San Jose State University, San Jose, California 95192, USA*
[29]*Sonoma State University, Rohnert Park, California 94928, USA*
[30]*Southeastern Louisiana University, Hammond, Louisiana 70402, USA*
[31]*Southern University and A&M College, Baton Rouge, Louisiana 70813, USA*
[32]*Stanford University, Stanford, California 94305, USA*
[33]*Syracuse University, Syracuse, New York 13244, USA*
[34]*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
[35]*The University of Texas at Austin, Austin, Texas 78712, USA*
[36]*The University of Texas at Brownsville and Texas Southmost College, Brownsville, Texas 78520, USA*
[37]*Trinity University, San Antonio, Texas 78212, USA*
[38]*Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain*
[39]*University of Adelaide, Adelaide, SA 5005, Australia*
[40]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[41]*University of Florida, Gainesville, Florida 32611, USA*
[42]*University of Glasgow, Glasgow, G12 8QQ, United Kingdom*
[43]*University of Maryland, College Park, Maryland 20742, USA*
[44]*University of Massachusetts, Amherst, Massachusetts 01003, USA*
[45]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[46]*University of Minnesota, Minneapolis, Minnesota 55455, USA*
[47]*University of Oregon, Eugene, Oregon 97403, USA*
[48]*University of Rochester, Rochester, New York 14627, USA*
[49]*University of Salerno, 84084 Fisciano (Salerno), Italy*
[50]*University of Sannio at Benevento, I-82100 Benevento, Italy*

[51]University of Southampton, Southampton, SO17 1BJ, United Kingdom
[52]University of Strathclyde, Glasgow, G1 1XQ, United Kingdom
[53]University of Western Australia, Crawley, Washington 6009, Australia
[54]University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA
[55]Washington State University, Pullman, Washington 99164, USA
[56]University of California-Berkeley, Space Sciences Lab, 7 Gauss Way, Berkeley, California 94720, USA
[57]Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA

S. Barthelmy,[58] N. Gehrels,[58] K. C. Hurley,[59] and D. Palmer[60]
[58]NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
[59]University of California-Berkeley, Space Sciences Lab, 7 Gauss Way, Berkeley, California 94720, USA
[60]Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA

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We present a LIGO search for short-duration gravitational waves (GWs) associated with soft gamma ray repeater (SGR) bursts. This is the first search sensitive to neutron star f modes, usually considered the most efficient GW emitting modes. We find no evidence of GWs associated with any SGR burst in a sample consisting of the 27 Dec. 2004 giant flare from SGR 1806−20 and 190 lesser events from SGR 1806−20 and SGR 1900+14. The unprecedented sensitivity of the detectors allows us to set the most stringent limits on transient GW amplitudes published to date. We find upper limit estimates on the model-dependent isotropic GW emission energies (at a nominal distance of 10 kpc) between 3×10^{45} and 9×10^{52} erg depending on waveform type, detector antenna factors and noise characteristics at the time of the burst. These upper limits are within the theoretically predicted range of some SGR models.

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Soft gamma ray repeaters (SGRs) sporadically emit brief (≈ 0.1 s) intense bursts of soft gamma rays with peak luminosities commonly up to 10^{42} erg/s [1,2]. Less common intermediate bursts with greater peak luminosities can last for seconds. Rare "giant flare" events, some 1000 times brighter than common bursts [3], have initial bright, short (≈ 0.2 s) pulses followed by tails lasting minutes and are among the most electromagnetically luminous events in the Universe [2]. Since the discovery of SGRs in 1979 three of the five confirmed SGRs have produced a giant flare each [4–7].

SGRs are promising sources of gravitational waves (GWs). According to the "magnetar" model SGRs are neutron stars with exceptionally strong magnetic fields $\sim 10^{15}$ G [8]. SGR bursts may result from the interaction of the star's magnetic field with its solid crust, leading to crustal deformations and occasional catastrophic cracking [9,10] with subsequent excitation of the star's nonradial modes [11–13] and the emission of GWs [12–14]. Excitation of nonradial modes could also occur if SGRs are instead solid quark stars [14–16].

We present a search for short-duration GW signals ($\lesssim 0.3$ s) associated with SGR bursts using data collected by the Laser Interferometer Gravitational Wave Observatory (LIGO) [17]. LIGO consists of two colocated GW detectors at Hanford, WA with baselines of 4 km and 2 km and one 4 km detector at Livingston, LA. GW data from one or two of these detectors are used. When three detectors are operating, data from the most sensitive pair are chosen.

The SGR burst sample was provided by gamma-ray satellites of the interplanetary network [18], and includes the 27 Dec. 2004 giant flare from SGR 1806−20 and 214 confirmed bursts (152 from SGR 1806−20 and 62 from SGR 1900+14, one of which was a multiepisodic "storm" [19]) occurring during the first year of LIGO's fifth science run (S5) from 14 Nov. 2005 to 14 Nov. 2006. Of the 214 bursts, 117 occurred with three LIGO detectors operating, 53 with two detectors operating, 20 with a single detector operating, and 24 with no detector operating. Including the giant flare, analysis was possible for a total of 191 listed SGR events.

To analyze a given SGR burst we divide the GW data into an on-source time region, in which GWs associated with the burst could be expected, and a background time region. In the background region we do not expect a GW associated with the SGR burst, but the noise is statistically similar to the on-source region. For isolated bursts the on-source region consists of 4 s of data centered on the SGR burst. GW emission is expected to occur almost simultaneously with the electromagnetic burst [13]; the 4 s on-source duration accounts for uncertainties in the geocentric electromagnetic peak time. There are three special cases: (1) for two SGR 1900+14 bursts which occurred within 4 s of each other a combined 7 s on-source region was chosen; (2) for the SGR 1900+14 storm a 40 s on-source region was used; (3) for a SGR 1806−20 event on 6 Aug. 2006 (hereafter 060806), two 4 s on-source regions were used, centered on the two distinct bright bursts comprising the event. Background regions consist of 1000 s of good data on either side of on-source regions. On-source and background segments are analyzed identically, including data quality cuts, resulting in lists of "analysis events." Analysis events from the background regions are used to estimate the significance of the on-source analysis events; significant events, if any, are subject to environmental vetoes and consistency checks.

The analysis is performed by the *flare pipeline* [20–22] and is based on the excess power detection statistic of [23]. Search parameters such as frequency bands and time windows are chosen to optimally detect the target signals. This is achieved by comparing detection efficiencies for simulated target signals injected into the background data and searched for with different search parameters [21]. The search targets neutron star fundamental mode ringdowns (RDs) predicted in [11–13,24,25] as well as unmodeled short-duration GW signals. Model predictions from [26] for ten realistic neutron star equations of state give f-mode RD frequencies in the range 1.5–3 kHz and damping times in the range 100–400 ms. We use a search band 1–3 kHz for RD searches (to include stiffer equations of state), and find a 250 ms time window to be optimal. The search for unmodeled signals uses time windows set by prompt SGR burst time scales (5–200 ms) and frequency bands set by the detector's sensitivity; a 125 ms time window effectively covers this duration range, and we search in two bands: 100–200 Hz (probing the region in which the detectors are most sensitive) and 100–1000 Hz (for full spectral coverage below the ringdown search band).

In the absence of a detection, for each SGR burst we estimate loudest event upper limits [27] on the GW strain incident on the detector, h_{rss}. Following [28] $h^2_{\mathrm{rss}} = h^2_{\mathrm{rss}+} + h^2_{\mathrm{rss}\times}$, where e.g. $h^2_{\mathrm{rss}+} = \int_{-\infty}^{\infty} h_+^2\,dt$ and $h_{+,\times}(t)$ are the two GW polarizations. The relationship between the GW polarizations and the detector response $h(t)$ to an impinging GW from an altitude and azimuth (θ, ϕ) and with polarization angle ψ is:

$$h(t) = F^+(\theta, \phi, \psi)h_+(t) + F^\times(\theta, \phi, \psi)h_\times(t), \qquad (1)$$

where $F^+(\theta, \phi, \psi)$ and $F^\times(\theta, \phi, \psi)$ are the antenna functions for the source at (θ, ϕ) [29]. The upper limit is computed in a frequentist framework following the commonly used procedure of injecting simulated signals in the data and recovering them using the search pipeline (see, for example, [30,31]). The upper limits are derived for RD signals and for unmodeled bursts. Correspondingly, RD and band-limited white noise burst (WNB) waveforms are injected with parameters chosen to probe the respective target signal space. For WNBs independent polarization components are generated with $h_{\mathrm{rss}+} = h_{\mathrm{rss}\times}$. For RD signals linearly and circularly polarized waves are considered. The polarization angle for each simulation was randomly chosen from a flat distribution between 0 and 2π.

The GW strain h_{rss} upper limits can be recast as upper limits on the emitted GW energy, E_{GW}. Assuming isotropic emission, the GW energy associated with $h_+(t)$ and $h_\times(t)$ is [32]:

$$E_{\mathrm{GW}} = 4\pi R^2 \frac{c^3}{16\pi G} \int_{-\infty}^{\infty} \Big((\dot{h}_+)^2 + (\dot{h}_\times)^2 \Big) dt. \qquad (2)$$

We use this equation with a nominal source distance of $R = 10$ kpc (source locations and distances are discussed in [33,34]) to compute the energies associated with the h_{rss} upper limits for different signals.

Results.—We find no evidence for gravitational waves associated with any of the SGR burst events in the sample. The significance of on-source analysis events is inferred by assigning rates at which background analysis events of equal or greater loudness occur. We find the most significant on-source analysis event occurs at a rate of 1.35×10^{-3} Hz (1 per 741 s), which is consistent with the expectation for the 803 s of on-source data in the sample. We estimate 90% confidence strain and energy upper limits, $h^{90\%}_{\mathrm{rss}}$ and $E^{90\%}_{\mathrm{GW}}$, using the loudest on-source analysis event for each SGR burst. Upper limits depend on detector

TABLE I. GW strain and energy upper limit estimates at 90% confidence ($h^{90\%}_{\mathrm{rss}}$ and $E^{90\%}_{\mathrm{GW}}$) for the SGR 1806−20 giant flare and the S5 SGR burst with the smallest limits on the ratio $\gamma = E^{90\%}_{\mathrm{GW}}/E_{\mathrm{EM}}$ for various circularly or linearly polarized RD (RDC/RDL) and white noise burst (WNB) waveforms. Uncertainties (given in superscripts for strain upper limits and explained in the text) are folded into the final upper limit estimates.

	SGR 1806−20 Giant Flare			SGR 1806−20 060806		
Waveform type	$h^{90\%}_{\mathrm{rss}}[10^{-22}\ \mathrm{Hz}^{-1/2}]$	$E^{90\%}_{\mathrm{GW}}$ [erg]	γ	$h^{90\%}_{\mathrm{rss}}[10^{-22}\ \mathrm{Hz}^{-1/2}]$	$E^{90\%}_{\mathrm{GW}}$ [erg]	γ
WNB 11 ms 100–200 Hz	$22^{+1.3+5.6+1.2} = 29$	7.3×10^{47}	5×10^1	$3.4^{+0.0+0.4+0.2} = 3.8$	1.3×10^{46}	4×10^3
WNB 100 ms 100–200 Hz	$18^{+1.1+4.6+0.5} = 24$	4.9×10^{47}	3×10^1	$2.9^{+0.0+0.3+0.1} = 3.3$	9.1×10^{45}	3×10^3
WNB 11 ms 100–1000 Hz	$50^{+3.0+13+1.3} = 66$	5.4×10^{49}	3×10^3	$7.5^{+0.0+0.8+0.3} = 8.3$	8.3×10^{47}	3×10^5
WNB 100 ms 100–1000 Hz	$45^{+2.7+12+1.1} = 59$	3.7×10^{49}	2×10^3	$7.0^{+0.1+0.7+0.2} = 7.9$	6.8×10^{47}	2×10^5
RDC 200 ms 1090 Hz	$59^{+3.6+15+1.7} = 78$	2.6×10^{50}	2×10^4	$10^{+0.2+1.1+0.4} = 12$	5.8×10^{48}	2×10^6
RDC 200 ms 1590 Hz	$93^{+5.6+24+2.8} = 120$	1.4×10^{51}	9×10^4	$15^{+0.6+1.5+0.5} = 17$	2.5×10^{49}	8×10^6
RDC 200 ms 2090 Hz	$120^{+7.4+32+3.5} = 160$	4.2×10^{51}	3×10^5	$20^{+1.6+2.5+0.6} = 24$	8.9×10^{49}	3×10^7
RDC 200 ms 2590 Hz	$150^{+9.1+39+4.1} = 200$	9.8×10^{51}	6×10^5	$24^{+3.1+3.0+0.9} = 30$	2.2×10^{50}	7×10^7
RDL 200 ms 1090 Hz	$170^{+10+44+36} = 240$	2.6×10^{51}	2×10^5	$33^{+1.0+3.4+3.5} = 38$	6.7×10^{49}	2×10^7
RDL 200 ms 1590 Hz	$260^{+16+68+32} = 360$	1.2×10^{52}	7×10^5	$44^{+2.2+4.6+6.3} = 54$	2.8×10^{50}	9×10^7
RDL 200 ms 2090 Hz	$390^{+23+99+46} = 520$	4.4×10^{52}	3×10^6	$64^{+7.0+8.1+9.1} = 83$	1.1×10^{51}	4×10^8
RDL 200 ms 2590 Hz	$440^{+26+110+63} = 600$	8.9×10^{52}	6×10^6	$79^{+10+10+9.7} = 100$	2.6×10^{51}	9×10^8

sensitivity and antenna factors at the time of the burst, the loudest on-source analysis event, and the simulation waveform type used.

Table I lists upper limits for the SGR 1806−20 giant flare and for the brightest peak of the 060806 event from SGR 1806−20 [35] (complete results are given in [36]). Results from these two events are highlighted because they yield the smallest values of $\gamma = E_{\rm GW}^{90\%}/E_{\rm EM}$, a measure of the extent to which an energy upper limit probes the GW emission efficiency. At the time of the giant flare the LIGO Hanford 4 km detector was operating during a commissioning period (LIGO Astrowatch) and had noise amplitude higher than that of S5 by a factor of 3; the rms antenna factor, which is an indicator of the average sensitivity to a given source in the sky, for such event was $(F_+^2 + F_\times^2)^{1/2} = 0.3$. The isotropic electromagnetic energy ($E_{\rm EM}$) for the event, assuming a distance of 10 kpc, was 1.6×10^{46} erg [6]. At the time of 060806 both the 4 km and 2 km Hanford detectors were observing, with rms antenna factor for that event of 0.5. $E_{\rm EM}$ for the brightest peak of 060806 was at least 2.9×10^{42} erg [35].

We estimate upper limits on GW strain and isotropic GW energy emitted using RDs with $\tau = 200$ ms at various frequencies, and WNBs lasting 11 and 100 ms and with 100–200 and 100–1000 Hz bands. We observe no more than 15% degradation in strain upper limits using RDs with τ in the range 100–300 ms, and no more than 20% degradation using WNBs with durations in the range 5–200 ms, as compared to the upper limits obtained for the nominal RDs and WNBs used for tuning the search. Superscripts in Table I give a systematic error and uncertainties at 90% confidence. The first and second superscripts account for systematic error and statistical uncertainty in amplitude and phase of the detector calibrations, estimated via Monte Carlo simulations, respectively. The third is a statistical uncertainty arising from using a finite number of injected simulations, estimated with the bootstrap method using 200 ensembles [37]. The systematic error and the quadrature sum of the statistical uncertainties are added to the final upper limit estimates.

Figure 1 shows $E_{\rm GW}^{90\%}$ limits for the entire SGR burst sample. The lowest upper limit in the sample, $E_{\rm GW}^{90\%} = 2.9 \times 10^{45}$ erg, is obtained for a SGR 1806−20 burst on 21 Jul. 2006, with a geocentric crossing time of 17:10:56.6 coordinated universal time (UTC). The lowest upper limit from the RD search is $E_{\rm GW}^{90\%} = 2.4 \times 10^{48}$ erg for a SGR 1806−20 burst on 24 Aug. 2006 14:55:26 UTC.

Discussion.—Two searches for GWs associated with SGR events have been published previously; neither claimed detection. The AURIGA collaboration searched for GW bursts associated with the SGR 1806−20 giant flare in the band 850–950 Hz with damping time 100 ms, setting upper limits on the GW energy of $\sim 10^{49}$ erg [38]. The LIGO collaboration also published on the same giant flare, targeting times and frequencies of the quasiperiodic oscillations in the flare's x-ray tail as well as other frequencies in the detector's band, and setting upper limits on GW energy as low as 8×10^{46} erg for quasiperiodic signals lasting tens of seconds [39].

In addition to the 2004 giant flare, the search described here covers 190 lesser events which occurred during the

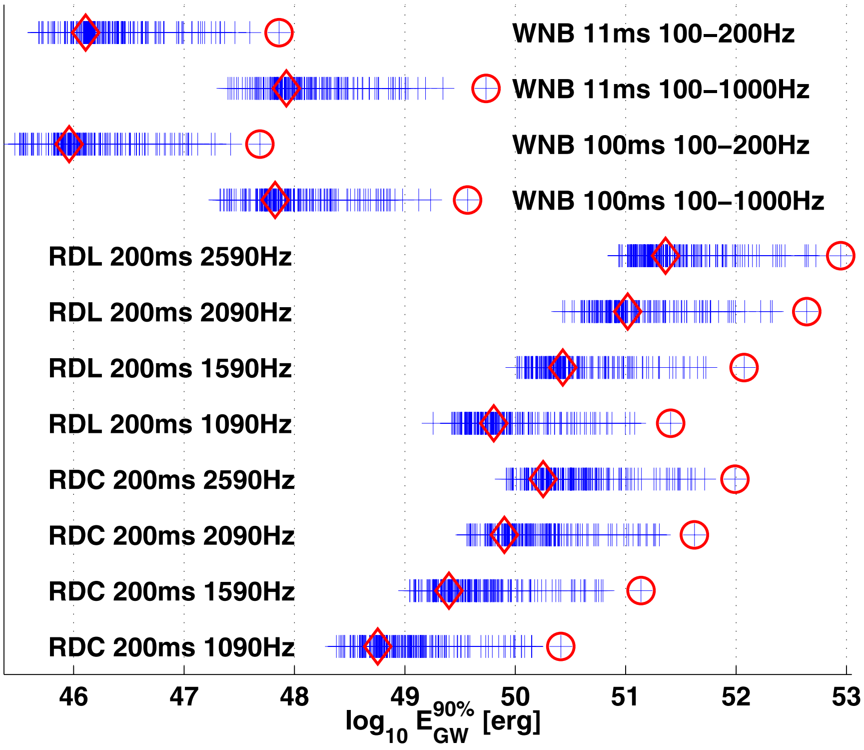

FIG. 1 (color online). $E_{\rm GW}^{90\%}$ upper limits for the entire SGR burst sample for various circularly or linearly polarized RDs (RDC/RDL) and white noise burst (WNB) signals. The limits shown in Table I, for the giant flare and the 060806 event, are indicated in the figure by circles and diamonds, respectively.

LIGO S5 data run. Furthermore this search extends to the entire high sensitivity band of the detectors, which makes it the first search sensitive to neutron star f modes, usually considered the most efficient GW emitting modes [11]. Our upper limits on E_{GW} overlap the range of E_{EM} 10^{44}–10^{46} erg seen in SGR giant flares [3,6]. Most of the WNB limits, and some of the RD limits, are below the 10^{49} erg maximum E_{GW} predicted in some theoretical models [13]. Our best upper limits on γ are within the theoretically predicted range implied in [13].

The Advanced LIGO detectors promise an improvement in h_{rss} by more than a factor of 10 over S5, corresponding to an improvement in energy sensitivity (and therefore γ) by more than a factor of 100. Thus within the next few years we expect to obtain GW energy upper limits for the f-mode search that fall in the E_{EM} range of giant flares, and for the unmodeled search that fall in the E_{EM} range of intermediate bursts.

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