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SEARCH FOR GRAVITATIONAL WAVE BURSTS FROM SIX MAGNETARS

J. Abadie[1], B. P. Abbott[1], R. Abbott[1], M. Abernathy[2], T. Accadia[3], F. Acernese[4ac], C. Adams[5], R. Adhikari[1], C. Affeldt[6,7], B. Allen[6,8,7], G. S. Allen[9], E. Amador Ceron[8], D. Amariutei[10], R. S. Amin[11], S. B. Anderson[1], W. G. Anderson[8], F. Antonucci[12a], K. Arai[1], M. A. Arain[10], M. C. Araya[1], S. M. Aston[13], P. Astone[12a], D. Atkinson[14], P. Aufmuth[7,6], C. Aulbert[6,7], B. E. Aylott[13], S. Babak[15], P. Baker[16], G. Ballardin[17], S. Ballmer[1], D. Barker[14], S. Barnum[18], F. Barone[4ac], B. Barr[2], P. Barriga[19], L. Barsotti[20], M. Barsuglia[21], M. A. Barton[14], I. Bartos[22], R. Bassiri[2], M. Bastarrika[2], A. Basti[23ab], J. Bauchrowitz[6,7], Th. S. Bauer[24a], B. Behnke[15], M.G. Beker[24a], A. S. Bell[2], A. Belletoile[3], I. Belopolski[22], M. Benacquista[25], A. Bertolini[6,7], J. Betzwieser[1], N. Beveridge[2], P. T. Beyersdorf[26], I. A. Bilenko[27], G. Billingsley[1], J. Birch[5], S. Birindelli[28a], R. Biswas[8], M. Bitossi[23a], M. A. Bizouard[29a], E. Black[1], J. K. Blackburn[1], L. Blackburn[20], D. Blair[19], B. Bland[14], M. Blom[24a], O. Bock[6,7], T. P. Bodiya[20], C. Bogan[6,7], R. Bondarescu[30], F. Bondu[28b], L. Bonelli[23ab], R. Bonnand[31], R. Bork[1], M. Born[6,7], V. Boschi[23a], S. Bose[32], L. Bosi[33a], B. Bouhou[21], M. Boyle[34], S. Braccini[23a], C. Bradaschia[23a], P. R. Brady[8], V. B. Braginsky[27], J. E. Brau[35], J. Breyer[6,7], D. O. Bridges[5], A. Brillet[28a], M. Brinkmann[6,7], V. Brisson[29a], M. Britzger[6,7], A. F. Brooks[1], D. A. Brown[36], A. Brummit[37], R. Budzyński[38b], T. Bulik[38cd], H. J. Bulten[24ab], A. Buonanno[39], J. Burguet–Castell[8], O. Burmeister[6,7], D. Buskulic[3], C. Buy[21], R. L. Byer[9], L. Cadonati[40], G. Cagnoli[41a], J. Cain[42], E. Calloni[4ab], J. B. Camp[43], E. Campagna[41ab], P. Campsie[2], J. Cannizzo[43], K. Cannon[1], B. Canuel[17], J. Cao[44], C. Capano[36], F. Carbognani[17], S. Caride[45], S. Caudill[11], M. Cavaglià[42], F. Cavalier[29a], R. Cavalieri[17], G. Cella[23a], C. Cepeda[1], E. Cesarini[41b], O. Chaibi[28a], T. Chalermsongsak[1], E. Chalkley[13], P. Charlton[46], E. Chassande-Mottin[21], S. Chelkowski[13], Y. Chen[34], A. Chincarini[47], N. Christensen[18], S. S. Y. Chua[48], C. T. Y. Chung[49], S. Chung[19], F. Clara[14], D. Clark[9], J. Clark[50], J. H. Clayton[8], F. Cleva[28a], E. Coccia[51ab], C. N. Colacino[23ab], J. Colas[17], A. Colla[12ab], M. Colombini[12b], R. Conte[52], D. Cook[14], T. R. Corbitt[20], N. Cornish[16], A. Corsi[12a], C. A. Costa[11], M. Coughlin[18], J.-P. Coulon[28a], D. M. Coward[19], D. C. Coyne[1], J. D. E. Creighton[8], T. D. Creighton[25], A. M. Cruise[13], R. M. Culter[13], A. Cumming[2], L. Cunningham[2], E. Cuoco[17], K. Dahl[6,7], S. L. Danilishin[27], R. Dannenberg[1], S. D'Antonio[51a], K. Danzmann[6,7], K. Das[10], V. Dattilo[17], B. Daudert[1], H. Daveloza[25], M. Davier[29a], G. Davies[50], E. J. Daw[53], R. Day[17], T. Dayanga[32], R. De Rosa[4ab], D. DeBra[9], G. Debreczeni[54], J. Degallaix[6,7], M. del Prete[23ac], T. Dent[50], V. Dergachev[1], R. DeRosa[11], R. DeSalvo[1], S. Dhurandhar[55], L. Di Fiore[4a], A. Di Lieto[23ab], I. Di Palma[6,7], M. Di Paolo Emilio[51ac], A. Di Virgilio[23a], M. Díaz[25], A. Dietz[3], F. Donovan[20], K. L. Dooley[10], S. Dorsher[56], E. S. D. Douglas[14], M. Drago[57cd], R. W. P. Drever[58], J. C. Driggers[1], J.-C. Dumas[19], S. Dwyer[20], T. Eberle[6,7], M. Edgar[2], M. Edwards[50], A. Effler[11], P. Ehrens[1], R. Engel[1], T. Etzel[1], M. Evans[20], T. Evans[5], M. Factourovich[22], V. Fafone[51ab], S. Fairhurst[50], Y. Fan[19], B. F. Farr[59], D. Fazi[59], H. Fehrmann[6,7], D. Feldbaum[10], I. Ferrante[23ab], F. Fidecaro[23ab], L. S. Finn[30], I. Fiori[17], R. Flaminio[31], M. Flanigan[14], S. Foley[20], E. Forsi[5], L. A. Forte[4a], N. Fotopoulos[8], J.-D. Fournier[28a], J. Franc[31], S. Frasca[12ab], F. Frasconi[23a], M. Frede[6,7], M. Frei[60], Z. Frei[61], A. Freise[13], R. Frey[35], T. T. Fricke[11], D. Friedrich[6,7], P. Fritschel[20], V. V. Frolov[5], P. Fulda[13], M. Fyffe[5], M. Galimberti[31], L. Gammaitoni[33ab], J. Garcia[14], J. A. Garofoli[36], F. Garufi[4ab], M. E. Gáspár[54], G. Gemme[47], E. Genin[17], A. Gennai[23a], S. Ghosh[32], J. A. Giaime[11,5], S. Giampanis[6,7], K. D. Giardina[5], A. Giazotto[23a], C. Gill[2], E. Goetz[45], L. M. Goggin[8], G. González[11], M. L. Gorodetsky[27], S. Gossler[6,7], R. Gouaty[3], C. Graef[6,7], M. Granata[21], A. Grant[2], S. Gras[19], C. Gray[14], R. J. S. Greenhalgh[37], A. M. Gretarsson[62], C. Greverie[28a], R. Grosso[25], H. Grote[6,7], S. Grunewald[15], G. M. Guidi[41ab], C. Guido[5], R. Gupta[55], E. K. Gustafson[1], R. Gustafson[45], B. Hage[7,6], J. M. Hallam[13], D. Hammer[8], G. Hammond[2], J. Hanks[14], C. Hanna[1], J. Hanson[5], J. Harms[58], G. M. Harry[20], I. W. Harry[50], E. D. Harstad[35], M. T. Hartman[10], K. Haughian[2], K. Hayama[63], J.-F. Hayau[28b], T. Hayler[37], J. Heefner[1], H. Heitmann[28], P. Hello[29a], M. A. Hendry[2], I. S. Heng[2], A. W. Heptonstall[1], V. Herrera[9], M. Hewitson[6,7], S. Hild[2], D. Hoak[40], K. A. Hodge[1], K. Holt[5], T. Hong[34], S. Hooper[19], D. J. Hosken[64], J. Hough[2], E. J. Howell[19], D. Huet[17], B. Hughey[20], S. Husa[65], S. H. Huttner[2], D. R. Ingram[14], R. Inta[48], T. Isogai[18], A. Ivanov[1], P. Jaranowski[38e], W. W. Johnson[11], D. I. Jones[66], G. Jones[50], R. Jones[2], L. Ju[19], P. Kalmus[1], V. Kalogera[59], S. Kandhasamy[56], J. B. Kanner[39], E. Katsavounidis[20], W. Katzman[5], K. Kawabe[14], S. Kawamura[63], F. Kawazoe[6,7], W. Kells[1], M. Kelner[59], D. G. Keppel[1], A. Khalaidovski[6,7], F. Y. Khalili[27], E. A. Khazanov[67], H. Kim[6,7], N. Kim[9], P. J. King[1], D. L. Kinzel[5], J. S. Kissel[11], S. Klimenko[10], V. Kondrashov[1], R. Kopparapu[30], S. Koranda[8], W. Z. Korth[1], I. Kowalska[38c], D. Kozak[1], V. Kringel[6,7], S. Krishnamurthy[59], B. Krishnan[15], A. Królak[38af], G. Kuehn[6,7], R. Kumar[2], P. Kwee[7,6], M. Landry[14], B. Lantz[9], N. Lastzka[6,7], A. Lazzarini[1], P. Leaci[15], J. Leong[6,7], I. Leonor[35], N. Leroy[29a], N. Letendre[3], J. Li[25], T. G. F. Li[24a], N. Liguori[57ab], P. E. Lindquist[1], N. A. Lockerbie[68], D. Lodhia[13], M. Lorenzini[41a], V. Loriette[29b], M. Lormand[5], G. Losurdo[41a], P. Lu[9], J. Luan[34], M. Lubinski[14], H. Lück[6,7], A. D. Lundgren[36], E. Macdonald[2], B. Machenschalk[6,7], M. MacInnis[20], M. Mageswaran[1], K. Mailand[1], E. Majorana[12a], I. Maksimovic[29b], N. Man[28a], I. Mandel[59], V. Mandic[56], M. Mantovani[23ac], A. Marandi[9], F. Marchesoni[33a], F. Marion[3], S. Márka[22], Z. Márka[22], E. Maros[1], J. Marque[17], F. Martelli[41ab], I. W. Martin[2], R. M. Martin[10], J. N. Marx[1], K. Mason[20], A. Masserot[3], F. Matichard[20], L. Matone[22], R. A. Matzner[60], N. Mavalvala[20], R. McCarthy[14], D. E. McClelland[48], S. C. McGuire[69], G. McIntyre[1], D. J. A. McKechan[50], G. Meadors[45], M. Mehmet[6,7], T. Meier[7,6], A. Melatos[49], A. C. Melissinos[70], G. Mendell[14], R. A. Mercer[8], L. Merill[19], S. Meshkov[1], C. Messenger[6,7], M. S. Meyer[5], H. Miao[19], C. Michel[31], L. Milano[4ab], J. Miller[2], Y. Minenkov[51a], Y. Mino[34], V. P. Mitrofanov[27], G. Mitselmakher[10], R. Mittleman[20], O. Miyakawa[63], B. Moe[8], P. Moesta[15], M. Mohan[17], S. D. Mohanty[25], S. R. P. Mohapatra[40], D. Moraru[14], G. Moreno[14], N. Morgado[31], A. Morgia[51ab], S. Mosca[4ab], V. Moscatelli[12a], K. Mossavi[6,7], B. Mours[3], C. M. Mow–Lowry[48], G. Mueller[10], S. Mukherjee[25], A. Mullavey[48], H. Müller-Ebhardt[6,7], J. Munch[64], P. G. Murray[2], T. Nash[1], R. Nawrodt[2], J. Nelson[2], I. Neri[33ab], G. Newton[2], E. Nishida[63], A. Nishizawa[63], F. Nocera[17], D. Nolting[5],

E. Ochsner[39], J. O'Dell[37], G. H. Ogin[1], R. G. Oldenburg[8], B. O'Reilly[5], R. O'Shaughnessy[30], C. Osthelder[1], C. D. Ott[34], D. J. Ottaway[64], R. S. Ottens[10], H. Overmier[5], B. J. Owen[30], A. Page[13], G. Pagliaroli[51ac], L. Palladino[51ac], C. Palomba[12a], Y. Pan[39], C. Pankow[10], F. Paoletti[23a,17], M. A. Papa[15,8], A. Parameswaran[1], S. Pardi[4ab], M. Parisi[4b], A. Pasqualetti[17], R. Passaquieti[23ab], D. Passuello[23a], P. Patel[1], D. Pathak[50], M. Pedraza[1], L. Pekowsky[36], S. Penn[71], C. Peralta[15], A. Perreca[13], G. Persichetti[4ab], M. Phelps[1], M. Pichot[28a], M. Pickenpack[6,7], F. Piergiovanni[41ab], M. Pietka[38e], L. Pinard[31], I. M. Pinto[72], M. Pitkin[2], H. J. Pletsch[6,7], M. V. Plissi[2], J. Podkaminer[71], R. Poggiani[23ab], J. Pöld[6,7], F. Postiglione[52], M. Prato[47], V. Predoi[50], L. R. Price[8], M. Prijatelj[6,7], M. Principe[72], S. Privitera[1], R. Prix[6,7], G. A. Prodi[57ab], L. Prokhorov[27], O. Puncken[6,7], M. Punturo[33a], P. Puppo[12a], V. Quetschke[25], F. J. Raab[14], D. S. Rabeling[24ab], I. Rácz[54], H. Radkins[14], P. Raffai[61], M. Rakhmanov[25], C. R. Ramet[5], B. Rankins[42], P. Rapagnani[12ab], V. Raymond[59], V. Re[51ab], K. Redwine[22], C. M. Reed[14], T. Reed[73], T. Regimbau[28a], S. Reid[2], D. H. Reitze[10], F. Ricci[12ab], R. Riesen[5], K. Riles[45], P. Roberts[74], N. A. Robertson[1,2], F. Robinet[29a], C. Robinson[50], E. L. Robinson[15], A. Rocchi[51a], S. Roddy[5], L. Rolland[3], J. Rollins[22], J. D. Romano[25], R. Romano[4ac], J. H. Romie[5], D. Rosińska[38g], C. Röver[6,7], S. Rowan[2], A. Rüdiger[6,7], P. Ruggi[17], K. Ryan[14], S. Sakata[63], M. Sakosky[14], F. Salemi[6,7], M. Salit[59], L. Sammut[49], L. Sancho de la Jordana[65], V. Sandberg[14], V. Sannibale[1], L. Santamaría[15], I. Santiago-Prieto[2], G. Santostasi[75], S. Saraf[76], B. Sassolas[31], B. S. Sathyaprakash[50], S. Sato[63], M. Satterthwaite[48], P. R. Saulson[36], R. Savage[14], R. Schilling[6,7], S. Schlamminger[8], R. Schnabel[6,7], R. M. S. Schofield[35], B. Schulz[6,7], B. F. Schutz[15,50], P. Schwinberg[14], J. Scott[2], S. M. Scott[48], A. C. Searle[1], F. Seifert[1], D. Sellers[5], A. S. Sengupta[1], D. Sentenac[17], A. Sergeev[67], D. A. Shaddock[48], M. Shaltev[6,7], B. Shapiro[20], P. Shawhan[39], T. Shihan Weerathunga[25], D. H. Shoemaker[20], A. Sibley[5], X. Siemens[8], D. Sigg[14], A. Singer[1], L. Singer[1], A. M. Sintes[65], G. Skelton[8], B. J. J. Slagmolen[48], J. Slutsky[11], J. R. Smith[77], M. R. Smith[1], N. D. Smith[20], R. Smith[13], K. Somiya[34], B. Sorazu[2], J. Soto[20], F. C. Speirits[2], L. Sperandio[51ab], M. Stefszky[48], A. J. Stein[20], J. Steinlechner[6,7], S. Steinlechner[6,7], S. Steplewski[32], A. Stochino[1], R. Stone[25], K. A. Strain[2], S. Strigin[27], A. S. Stroeer[43], R. Sturani[41ab], A. L. Stuver[5], T. Z. Summerscales[74], M. Sung[11], S. Susmithan[19], P. J. Sutton[50], B. Swinkels[17], G. P. Szokoly[61], D. Talukder[32], D. B. Tanner[10], S. P. Tarabrin[6,7], J. R. Taylor[6,7], R. Taylor[1], P. Thomas[14], K. A. Thorne[5], K. S. Thorne[34], E. Thrane[56], A. Thüring[7,6], C. Titsler[30], K. V. Tokmakov[68], A. Toncelli[23ab], M. Tonelli[23ab], O. Torre[23ac], C. Torres[5], C. I. Torrie[1,2], E. Tournefier[3], F. Travasso[33ab], G. Traylor[5], M. Trias[65], K. Tseng[9], L. Turner[1], D. Ugolini[78], K. Urbanek[9], H. Vahlbruch[7,6], B. Vaishnav[25], G. Vajente[23ab], M. Vallisneri[34], J. F. J. van den Brand[24ab], C. Van Den Broeck[50], S. van der Putten[24a], M. V. van der Sluys[59], A. A. van Veggel[2], S. Vass[1], M. Vasuth[54], R. Vaulin[8], M. Vavoulidis[29a], A. Vecchio[13], G. Vedovato[57c], J. Veitch[50], P. J. Veitch[64], C. Veltkamp[6,7], D. Verkindt[3], F. Vetrano[41ab], A. Viceré[41ab], A. E. Villar[1], J.-Y. Vinet[28a], H. Vocca[33a], C. Vorvick[14], S. P. Vyachanin[27], S. J. Waldman[20], L. Wallace[1], A. Wanner[6,7], R. L. Ward[21], M. Was[29a], P. Wei[36], M. Weinert[6,7], A. J. Weinstein[1], R. Weiss[20], L. Wen[34,19], S. Wen[5], P. Wessels[6,7], M. West[36], T. Westphal[6,7], K. Wette[6,7], J. T. Whelan[79], S. E. Whitcomb[1], D. White[53], B. F. Whiting[10], C. Wilkinson[14], P. A. Willems[1], H. R. Williams[30], L. Williams[10], B. Willke[6,7], L. Winkelmann[6,7], W. Winkler[6,7], C. C. Wipf[20], A. G. Wiseman[8], G. Woan[2], R. Wooley[5], J. Worden[14], J. Yablon[59], I. Yakushin[5], H. Yamamoto[1], K. Yamamoto[6,7], H. Yang[34], D. Yeaton-Massey[1], S. Yoshida[80], P. Yu[8], M. Yvert[3], M. Zanolin[62], L. Zhang[1], Z. Zhang[19], C. Zhao[19], N. Zotov[73], M. E. Zucker[20], J. Zweizig[1]
The LIGO Scientific Collaboration and the Virgo Collaboration

R. L. Aptekar[81], W. V. Boynton[82], T. L. Cline[43], D. D. Frederiks[81], J. O Goldsten[83], D. Golovin[84], A.J. van der Horst[85], K. C. Hurley[86], Y. Kaneko[87], A. von Kienlin[88], C. Kouveliotou[89], L. Lin[93,94], I. Mitrofanov[84], M. Ohno[90], V. D. Pal'shin[81], A. Rau[89], A. Sanin[84], M. S. Tashiro[91], Y. Terada[91], and K. Yamaoka[92]

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ABSTRACT

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are thought to be magnetars: neutron stars powered by extreme magnetic fields. These rare objects are characterized by repeated and sometimes spectacular gamma-ray bursts. The burst mechanism might involve crustal fractures and excitation of non-radial modes which would emit gravitational waves (GWs). We present the results of a search for GW bursts from six galactic magnetars that is sensitive to neutron star f-modes, thought to be the most efficient GW emitting oscillatory modes in compact stars. One of them, SGR 0501+4516, is likely $\sim 1\,\mathrm{kpc}$ from Earth, an order of magnitude closer than magnetars targeted in previous GW searches. A second, AXP 1E 1547.0−5408, gave a burst with an estimated isotropic energy $> 10^{44}$ erg which is comparable to the giant flares. We find no evidence of GWs associated with a sample of 1279 electromagnetic triggers from six magnetars occurring between November 2006 and June 2009, in GW data from the LIGO, Virgo, and GEO600 detectors. Our lowest model-dependent GW emission energy upper limits for band- and time-limited white noise bursts in the detector sensitive band, and for f-mode ringdowns (at 1090 Hz), are $3.0 \times 10^{44} d_1^2$ erg and $1.4 \times 10^{47} d_1^2$ erg respectively, where $d_1 = \frac{d_{0501}}{1\,\mathrm{kpc}}$ and d_{0501} is the distance to SGR 0501+4516. These limits on GW emission from f-modes are an order of magnitude lower than any previous, and approach the range of electromagnetic energies seen in SGR giant flares for the first time.

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[1] LIGO - California Institute of Technology, Pasadena, CA 91125, USA

[2] University of Glasgow, Glasgow, G12 8QQ, United Kingdom
[3] Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
[4] INFN, Sezione di Napoli [a]; Università di Napoli 'Federico II'[b] Complesso Universitario di Monte S.Angelo, I-80126 Napoli; Università di Salerno, Fisciano, I-84084 Salerno[c], Italy
[5] LIGO - Livingston Observatory, Livingston, LA 70754, USA
[6] Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany
[7] Leibniz Universität Hannover, D-30167 Hannover, Germany
[8] University of Wisconsin–Milwaukee, Milwaukee, WI 53201, USA
[9] Stanford University, Stanford, CA 94305, USA
[10] University of Florida, Gainesville, FL 32611, USA
[11] Louisiana State University, Baton Rouge, LA 70803, USA
[12] INFN, Sezione di Roma[a]; Università 'La Sapienza'[b], I-00185 Roma, Italy
[13] University of Birmingham, Birmingham, B15 2TT, United Kingdom
[14] LIGO - Hanford Observatory, Richland, WA 99352, USA
[15] Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Golm, Germany
[16] Montana State University, Bozeman, MT 59717, USA
[17] European Gravitational Observatory (EGO), I-56021 Cascina (PI), Italy
[18] Carleton College, Northfield, MN 55057, USA
[19] University of Western Australia, Crawley, WA 6009, Australia
[20] LIGO - Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[21] Laboratoire AstroParticule et Cosmologie (APC) Université Paris Diderot, CNRS: IN2P3, CEA: DSM/IRFU, Observatoire de Paris, 10 rue A.Domon et L.Duquet, 75013 Paris - France
[22] Columbia University, New York, NY 10027, USA
[23] INFN, Sezione di Pisa[a]; Università di Pisa[b]; I-56127 Pisa; Università di Siena, I-53100 Siena[c], Italy
[24] Nikhef, Science Park, Amsterdam, the Netherlands[a]; VU University Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, the Netherlands[b]
[25] The University of Texas at Brownsville and Texas Southmost College, Brownsville, TX 78520, USA
[26] San Jose State University, San Jose, CA 95192, USA
[27] Moscow State University, Moscow, 119992, Russia
[28] Université Nice-Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, F-06304 Nice[a]; Institut de Physique de Rennes, CNRS, Université de Rennes 1, 35042 Rennes[b], France
[29] LAL, Université Paris-Sud, IN2P3/CNRS, F-91898 Orsay[a]; ESPCI, CNRS, F-75005 Paris[b], France
[30] The Pennsylvania State University, University Park, PA 16802, USA
[31] Laboratoire des Matériaux Avancés (LMA), IN2P3/CNRS, F-69622 Villeurbanne, Lyon, France
[32] Washington State University, Pullman, WA 99164, USA
[33] INFN, Sezione di Perugia[a]; Università di Perugia[b], I-06123 Perugia,Italy
[34] Caltech-CaRT, Pasadena, CA 91125, USA
[35] University of Oregon, Eugene, OR 97403, USA
[36] Syracuse University, Syracuse, NY 13244, USA
[37] Rutherford Appleton Laboratory, HSIC, Chilton, Didcot, Oxon OX11 0QX United Kingdom
[38] IM-PAN 00-956 Warsaw[a]; Warsaw University 00-681 Warsaw[b]; Astronomical Observatory Warsaw University 00-478 Warsaw[c]; CAMK-PAN 00-716 Warsaw[d]; Białystok University 15-424 Białystok[e]; IPJ 05-400 Świerk-Otwock[f]; Institute of Astronomy 65-265 Zielona Góra[g], Poland
[39] University of Maryland, College Park, MD 20742 USA
[40] University of Massachusetts - Amherst, Amherst, MA 01003, USA
[41] INFN, Sezione di Firenze, I-50019 Sesto Fiorentino[a]; Università degli Studi di Urbino 'Carlo Bo', I-61029 Urbino[b], Italy
[42] The University of Mississippi, University, MS 38677, USA
[43] NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[44] Tsinghua University, Beijing 100084 China
[45] University of Michigan, Ann Arbor, MI 48109, USA
[46] Charles Sturt University, Wagga Wagga, NSW 2678, Australia
[47] INFN, Sezione di Genova; I-16146 Genova, Italy
[48] Australian National University, Canberra, 0200, Australia
[49] The University of Melbourne, Parkville VIC 3010, Australia
[50] Cardiff University, Cardiff, CF24 3AA, United Kingdom
[51] INFN, Sezione di Roma Tor Vergata[a]; Università di Roma Tor Vergata, I-00133 Roma[b]; Università dell'Aquila, I-67100 L'Aquila[c], Italy
[52] University of Salerno, I-84084 Fisciano (Salerno), Italy and INFN (Sezione di Napoli), Italy
[53] The University of Sheffield, Sheffield S10 2TN, United Kingdom
[54] RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
[55] Inter-University Centre for Astronomy and Astrophysics, Pune - 411007, India
[56] University of Minnesota, Minneapolis, MN 55455, USA
[57] INFN, Gruppo Collegato di Trento[a] and Università di Trento[b], I-38050 Povo, Trento, Italy; INFN, Sezione di Padova[c] and Università di Padova[d], I-35131 Padova, Italy
[58] California Institute of Technology, Pasadena, CA 91125, USA
[59] Northwestern University, Evanston, IL 60208, USA
[60] The University of Texas at Austin, Austin, TX 78712, USA
[61] Eötvös Loránd University, Budapest, 1117 Hungary
[62] Embry-Riddle Aeronautical University, Prescott, AZ 86301 USA
[63] National Astronomical Observatory of Japan, Tokyo 181-8588, Japan
[64] University of Adelaide, Adelaide, SA 5005, Australia
[65] Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
[66] University of Southampton, Southampton, SO17 1BJ, United Kingdom
[67] Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
[68] University of Strathclyde, Glasgow, G1 1XQ, United Kingdom
[69] Southern University and A&M College, Baton Rouge, LA 70813, USA
[70] University of Rochester, Rochester, NY 14627, USA
[71] Hobart and William Smith Colleges, Geneva, NY 14456, USA
[72] University of Sannio at Benevento, I-82100 Benevento, Italy and INFN (Sezione di Napoli), Italy
[73] Louisiana Tech University, Ruston, LA 71272, USA
[74] Andrews University, Berrien Springs, MI 49104 USA
[75] McNeese State University, Lake Charles, LA 70609 USA
[76] Sonoma State University, Rohnert Park, CA 94928, USA
[77] California State University Fullerton, Fullerton CA 92831 USA
[78] Trinity University, San Antonio, TX 78212, USA
[79] Rochester Institute of Technology, Rochester, NY 14623, USA
[80] Southeastern Louisiana University, Hammond, LA 70402,

1. INTRODUCTION

Magnetars are isolated neutron stars (NS) powered by extreme magnetic fields ($\sim 10^{15}$ G) (Duncan & Thompson 1992). The magnetar model explains the observed properties of two classes of rare objects, the soft gamma repeaters (SGRs) and the anomalous X-ray pulsars (AXPs): compact X-ray sources with long rotation periods and rapid spindowns which sporadically emit short (≈ 0.1 s) bursts of soft gamma rays (for a review see Mereghetti 2008.) Fewer than twenty SGRs and AXPs are known. The total isotropic burst energies rarely exceed 10^{42} erg. However, three extraordinary "giant flares" have been observed in ∼30 years from SGRs in our galaxy and the Large Magellanic Cloud: one from SGR 0526−66 in 1979 with an observed total isotropic energy of $\sim 1.2\times10^{44} d_{55}^2$ erg (Mazets et al. 1979); one from SGR 1900+14 in 1998 with $4.3\times10^{44} d_{15}^2$ erg (Tanaka et al. 2007); and a spectacular one from SGR 1806−20 in 2004 with $\sim 5\times10^{46} d_{15}^2$ erg (Terasawa et al. 2005) where $d_n = d/(n\,\mathrm{kpc})$. There is also evidence that some short gamma ray bursts (GRBs) were in fact extragalactic giant flares. GRB 070201 might have been a giant flare located in the Andromeda galaxy with an isotropic energy of 1.5×10^{45} erg (Mazets et al. 2008; Abbott et al. 2008a); and GRB 051103 might have been a giant flare in M81 with an energy of 7.5×10^{46} erg (Frederiks et al. 2007).

Although still poorly understood, magnetars are promising candidates for the first direct gravitational wave (GW) detection for several reasons. First, a sudden localized energy release could excite non-radial pulsational NS modes. Bursts may be caused by untwisting of the global interior magnetic field and associated cracking of the solid NS crust (Thompson & Duncan 1995), or global reconfiguration of the internal magnetic field and associated deformation of the NS hydrostatic equilibrium (Ioka 2001). The lowest- order GW emitting mode, the f-mode, is damped principally via GW emission and would ring down with a predicted damping time of 100–400 ms and with a frequency in the 1–3 kHz range depending on the nuclear equation of state and NS composition (Benhar et al. 2004), putting these signals in the band of ground-based interferometric GW detectors (see Figure 1). Second, precise sky locations and trigger times from electromagnetic (EM) bursts allow us to reduce the false-alarm rate and increase sensitivity relative to all-sky all-time searches such as Abadie et al. (2010). Finally, magnetars are among the closest of potential GW burst sources.

It may turn out that the magnetar burst mechanism does not excite global NS f-modes. If the outburst dynamics are confined to the surface layer modes, the crust torsional oscillations might emit GWs at frequencies of $\sim 10-2000$ Hz (McDermott et al. 1988). There is also a possibility that although the crust is a plausible site for triggering, magnetar bursts are confined to the magnetosphere(Lyutikov 2006), although even in this case f-modes might be excited either directly or via hydromagnetic coupling between the crust and the core. Finally we note that it is not yet clear if giant flares and common bursts are caused by the same mechanism. The lack of theoretical understanding underlines the importance of placing observational constraints on GW emission.

We present results from a search for GW bursts associated with magnetar EM bursts using data from the second year of LIGO's fifth science run (S5y2, Abbott et al. 2009a); Virgo's first science run (VSR1, Acernese et al. 2008); and the subsequent LIGO and GEO *astrowatch* period (A5), during which the principal goal was detector commissioning, not data collection. The S5y2 epoch involved the three LIGO detectors: a 4 km interferometer in Louisiana and two interferometers (4 km and 2 km) in Washington. The VSR1 epoch added the Virgo 3 km detector to the global network. The A5 epoch included only the LIGO 2 km detector and the GEO 600 m detector (Lück et al. 2006). The Virgo and GEO600 detectors are located in Italy and Germany, respectively.

This is the third search for GWs from magnetars sensitive to f-mode ringdowns. The first such search (Abbott et al. 2008b) included the 2004 SGR 1806−20 giant flare, a 2006 storm of bursts from SGR 1900+14, and 188 other events from SGRs 1806−20 and 1900+14 occurring before November 2006. Upper limits on f-mode GW energy emission at 1090 Hz ranged from 2.4×10^{48} erg to 2.6×10^{51} erg, and upper limits on band- and time-limited white noise bursts at 100–200 Hz ranged from 3.1×10^{45} erg to 7.3×10^{47} erg. The second search sensitive to f-modes (Abbott et al. 2009b) focused on the 2006 SGR 1900+14 storm, "stacking" GW data corresponding to individual bursts in the storm's EM lightcurve (Kalmus et al. 2009). An upper limit on f-mode emission at 1090 Hz of 1.2×10^{48} erg per burst was set on a stack of the 11 brightest bursts in the storm, an order of magnitude lower than the previous limit on GW emission associated with the storm.

During the S5y2, VSR1 and A5 epochs of the search we present here, 1217 soft gamma-ray bursts from six magnetar sources were listed by the interplanetary network of satellites [95] or IPN (Table 1 and Figure 2).

USA
[81] Ioffe Physico-Technical Institute, Russian Academy of Science, St.Petersburg, 194021, Russia
[82] Department of Planetary Sciences, University of Arizona, Tucson AZ 85721, USA
[83] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[84] Institute for Space Research, Profsojuznaja 84/32 117997 Moscow, Russia
[85] NASA Postdoctoral Program Fellow, NASA Marshall Space Flight Center, Huntsville, AL 35805, USA
[86] University of California-Berkeley, Space Sciences Lab, 7 Gauss Way, Berkeley, CA 94720, USA
[87] SabancıUniversity, Orhanlı-Tuzla 34956 İstanbul, Turkey
[88] Max-Planck Institut für extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany
[89] Space Science Office, VP62, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
[93] The National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[94] SPAR, University of Alabama in Huntsville, Huntsville, Alabama, USA
[90] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku Sagamihara, Kanagawa 252-5120, Japan
[91] Department of Physics, Saitama University, 255 Shimo-Okubo, Sakura, Saitama, 338-8570, Japan
[92] Department of Physics and Mathematics, Aoyama Gakuin University, 5-10-1 Fuchinobe, Chuo-ku, Sagamihara, Kanagawa 252-5258, Japan

[95] http://ssl.berkeley.edu/ipn3

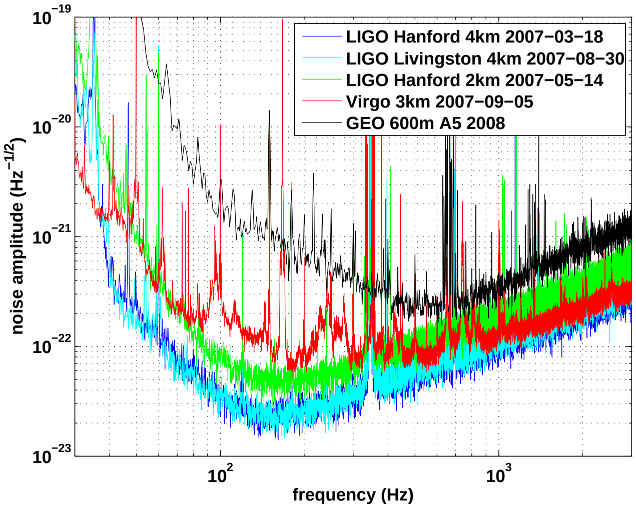

FIG. 1.— Best detector noise spectra from the LIGO and Virgo detectors during S5/VSR1 and the GEO600 detector during A5.

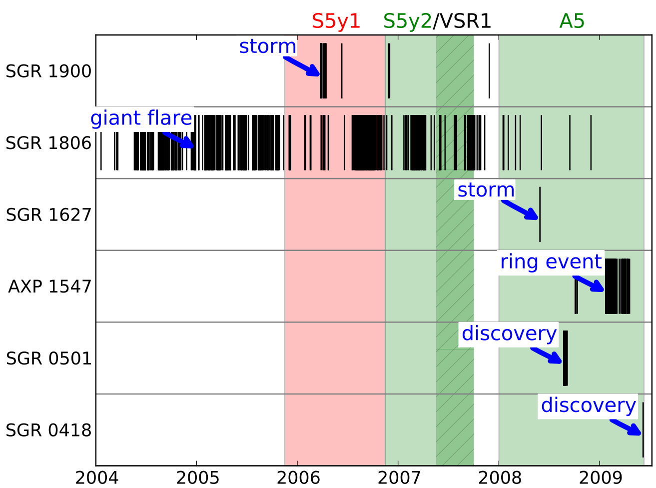

FIG. 2.— Each mark represents a burst from one of the six magnetar sources. Exceptional events are annotated in the figure; SGR 0501+4516 and SGR 0481+5279 were discovered in the A5 epoch. The LIGO S5y1 epoch was the subject of the first f- mode search (Abbott et al. 2008b). The current search includes bursts which occurred during the LIGO S5y2 and Virgo VSR1 epochs for which usable data were available, as well as the A5 astrowatch commissioning period. The VSR1 epoch, which is a subset of the S5y2 epoch, is indicated by cross-hatching and darker shading. (NB: unabbreviated source names are given in Table 1.)

Four of the sources are being examined for GW signals for the first time. Two of those (SGR 0501+4516 and SGR 0418+5729) are thought to be much closer to Earth than SGRs examined in previous GW searches. SGR 0501+4516 might be associated with the supernova remnant HB9 (Gaensler & Chatterjee 2008), which is (800 ± 400) pc from Earth (Leahy & Tian 2007); proper motion measurements could exclude this association. The probable locations of both SGR 0501+4516 and SGR 0418+5729 in the Perseus arm of our galaxy imply distances of ∼1–2 kpc van der Horst et al. (2010). AXP 1E 1547.0−5408 (also known as SGR 1550–5418) gave two exceptional bursts on 2009 January 22. Observations of expanding rings around the source, caused by X-ray scattering off dust sheets, set the source distance at 4–5 kpc and imply an EM energy for one or both of these bursts of 10^{44-45} erg (Tiengo et al. 2010). In addition to the IPN triggers, we include 8 additional triggers from the Fermi GBM detector: seven from bright bursts from AXP 1E 1547.0−5408 and one from an SGR 0418+5729 burst. We also identified 54 individual peaks in a storm from SGR 1627−41 lasting ∼ 2000 s (Israel et al. 2008). This was done by combining the 15–25 keV and 25–50 keV Swift/BAT 64 ms-binned light curves[96 97] and selecting peaks above 450 counts / 64 ms. The search thus includes a grand total of 1279 EM triggers.

2. METHOD

We analyze magnetar bursts individually using the strategy from Abbott et al. (2008b), which is less dependent on a particular emission model than the stacking approach of Abbott et al. (2009b). The analysis is performed by the Flare pipeline (Kalmus et al. 2007; Kalmus 2008), a simple but effective excess power analysis code. Flare produces a time-frequency pixel map from calibrated detector data streams in the Fourier basis. Pixels are characterized by excess power relative to the background (“loudness”). Loud pixels are grouped via density-based clustering to produce “events.” An event’s loudness is the sum over its component pixels. The generalized pipeline accepts arbitrary networks of GW detectors by including detector noise floor measurements and antenna responses to the source sky location in the detection statistic (Kalmus 2010). We divide the search into three frequency bands: 1–3 kHz where f-modes are predicted to ring; and 100–200 Hz and 100–1000 Hz. We include the latter two frequency bands in order to search also at lower frequencies where the detectors are most sensitive (see Figure 1). Although there are no predictions of GW *burst* signals from magnetars at these lower frequencies, we note that quasiperiodic oscillations (QPOs), lasting for tens of seconds and possibly associated with stellar torsional modes, have been observed in giant flare EM tails at frequencies as low as 18 Hz and as high as 1800 Hz (Strohmayer & Watts 2005; Steiner & Watts 2009). QPOs in the tail of the 2004 giant flare were targeted by a tailored GW search(Abbott et al. 2007) distinct from the one presented here.

As in Abbott et al. (2008b), we choose 4 s signal regions centered on each EM trigger time. Delays between EM and GW emission are unlikely to be significant (Kalmus et al. 2009); the 4 s duration accounts for uncertainties in the geocentric EM peak time due e.g. to satellite triggering algorithms and rounding. Overlapping signal regions are merged. We analyze 1000 s of background on either side of each signal region (2000 s total) in order to estimate the significance of events in that signal region. Background regions are not necessarily continuous, as we require the same detector network coverage and

[96] http://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/2008_05/00312582000
[97] http://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/2008_05/00090056009

TABLE 1
Summary of source sky locations and estimated distances. The nominal distances d_N are the distance used in the search for setting upper limits. Energy upper limits can be scaled to any distance d via the factor d^2/d_N^2. Some EM triggers occurred when there was no GW data available (i.e. $N = 0$).

Source	Position J2000	Distances (kpc) Estimated	Nominal	EM triggers total	Analyzed with N detectors $N=1$	$N=2$	$N\geq 3$
SGR 0418+5729[a]	$04^{\rm h}18^{\rm m}33.867 \pm 0.35^{\rm s}$ $+57°32'22.91 \pm 0.35''$	∼2	∼2	3	3	-	-
SGR 0501+4516[b]	$05^{\rm h}01^{\rm m}06.8 \pm 1.4^{\rm s}$ $+45°16'35.4 \pm 1.4''$	∼2, 0.8±0.4	1	166	105	24	-
AXP 1E 1547.0−5408[c]	$15^{\rm h}50^{\rm m}54.11 \pm 0.01^{\rm s}$ $-54°18'23.7 \pm 0.1''$	4-5, 9, 4	4	844	315	512	-
SGR 1627–41[d]	$16^{\rm h}35^{\rm m}51.84 \pm 0.2^{\rm s}$ $-47°35'23.31 \pm 0.2''$	11±0.3	11	56	-	56	-
SGR 1806−20[e]	$18^{\rm h}08^{\rm m}39.32 \pm 0.3^{\rm s}$ $-20°24'39.5 \pm 0.3''$	$8.7^{+1.8}_{-1.5}$, 6.4–9.8, $15.1^{+1.8}_{-1.3}$	10	207	11	36	136
SGR 1900+14[f]	$19^{\rm h}07^{\rm m}14.33 \pm 0.15^{\rm s}$ $+09°19'20.1 \pm 0.15''$	3–9, 12–15, 5	10	3	-	1	-

[a]position: Woods et al. (2009); distance: Esposito et al. (2010); van der Horst et al. (2010)
[b]position: Evans & Osborne (2008); distance: van der Horst et al. (2010); Gaensler & Chatterjee (2008); Leahy & Tian (2007)
[c]position: Camilo et al. (2007); distance: Tiengo et al. (2010); Camilo et al. (2007); Gelfand & Gaensler (2007)
[d]position: Wachter et al. (2004); distance: Corbel et al. (1999)
[e]position: Kaplan et al. (2002); distance: Bibby et al. (2008); Cameron et al. (2005); Corbel & Eikenberry (2004)
[f]position: Frail et al. (1999); distance: Marsden et al. (2001); Vrba et al. (2000); Vasisht et al. (1994)

data quality as for the signal region; in addition, signal regions of other magnetar bursts are masked out. Signal and background regions are chosen after data quality cuts have been applied to the GW data, so as to remove data segments coincident with instrumental or data acquisition problems, or excessive noise due to challenging environmental conditions. For the S5y2 portion of this search, we applied category 1 and 2 data quality cuts (i.e. cutting only data certain to be unfit for analysis) as described in Abadie et al. (2010). For A5, which focused on detector commissioning, the boolean "science mode" designator and other basic data quality treatments were applied to the data, but the full categorical data quality treatment was not performed. Statistically significant events in the signal regions from any epoch are subject to follow-up investigations before being considered detection candidates. Follow-ups might include correlation with environmental data channels and more refined estimates of significance.

Independent of any detection candidate, we use the loudest event in the signal region to set 90% detection efficiency upper limits on both the GW strain incident on the detector, and on the isotropic GW emission energy. That is, we set model dependent upper limits on eight NS f-mode ringdowns with circular and linear polarizations, frequencies of 1090 Hz, 1590 Hz, 2090 Hz, and 2590 Hz, and a decay time constant $\tau = 200$ ms; and also on band- and time-limited white noise bursts with 11 ms and 100 ms durations (motivated by observed rise times and durations of magnetar burst light curves) spanning the 100–200 Hz and 100–1000 Hz search bands in the detectors' most sensitive region below the f-mode frequencies. Simulations of these types of GW signals are injected into the background to measure detection efficiency relative to the loudest signal region event.

Simulations are constructed using knowledge of the target magnetar's sky location and the EM burst time. Following Abbott et al. (2008b), $h_{\rm rss}^2 = h_{\rm rss+}^2 + h_{\rm rss\times}^2$, where $h_{\rm rss+,\times}^2 = \int_{-\infty}^{\infty} h_{+,\times}^2 {\rm d}t$ and $h_{+,\times}(t)$ are the two GW polarizations. The relationship between the GW polarizations and the detector response $h(t)$ to GW signals arriving 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) (Thorne 1987). As before, the polarization angle for each simulation of the detector response to a signal, $h(t)$, was randomly chosen from a flat distribution between 0 and 2π. The GW emission energy (if the integrand is averaged over inclination angle) is

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

In order to obtain model-dependent upper limits on $E_{\rm GW}$ or $h_{\rm rss}$ for a given signal region we proceed as follows:

(1) We determine the loudest event in the signal region.
(2) For a specific simulated signal type, we inject a simulation at a specific $E_{\rm GW}$ and $h_{\rm rss}$ in a randomly selected 4 s interval of the background data and use the Flare pipeline to find events in that region. We compare the loudest signal region event to the loudest event with a cluster centroid time near the known injection time (within 100 ms for ringdowns and within 50 ms for white noise bursts).
(3) We repeat (2) for a range of $E_{\rm GW}$ and $h_{\rm rss}$ values, and at each value we determine the fraction of injections with associated events louder than the loudest signal region event.
(4) We repeat (3) using different simulated signal types. For each signal type, we estimate the 90% detection efficiency loudest event upper limit, $E_{\rm GW}^{90\%}$ or $h_{\rm rss}^{90\%}$, at which 90% of injection events would be louder than the loudest signal region event.

3. RESULTS AND DISCUSSION

We find no evidence of a GW signal in any of the signal regions analyzed. The loudest event of the search occurred at 2009 January 22 05:48:43.2 UTC and was the only event with a false-alarm rate below our predetermined follow-up threshold of $1/(3 \times 4808\,\mathrm{s}) = 6.9 \times 10^{-5}$ Hz as estimated via extrapolation from the 2000 s local background region. This event cannot be considered a GW candidate because it was found when only the Hanford 2 km detector was observing and was coincident with a strong glitch caused by fluctuations in the AC power picked up by a magnetometer, and thus is highly likely to be an instrumental artifact.

We estimate $h_{\mathrm{rss}}^{90\%}$ and $E_{\mathrm{GW}}^{90\%}$ for each signal region, which depend on detector sensitivities and antenna factors at the time of the burst, the loudest signal region event, and the simulation waveform type used. $E_{\mathrm{GW}}^{90\%}$ upper limits also depend on nominal source distance d_{N} and can be scaled to any source distance d via the factor $(d/d_{\mathrm{N}})^2$.

Figure 3 shows E_{GW} upper limits for each of the EM triggers from the six magnetar candidates, for each waveform type. The complete table of upper limits is online[98]. We spotlight electromagnetically bright bursts from SGR 0501+4516 and AXP 1E 1547.0−5408; however since detailed source models are lacking E_{EM} and E_{GW} may not be correlated. Table 2 presents E_{GW} and h_{rss} upper limits for three exceptional EM triggers; and for a burst from SGR 0501+4516 occurring in the signal region centered at 2008 August 23 16:31:22 UTC which yielded the lowest upper limits of the search. Each was analyzed with a two-detector network consisting of the LIGO 2 km and GEO600 detectors. The SGR 0501+4516 burst with the largest EM fluence (2.21×10^{-5} erg/cm ^{2} (Aptekar et al. 2009), which corresponds to a 1 kpc isotropic energy of 2.7×10^{39} erg) occurred in the signal region centered at 2008 August 24 01:17:58 UTC. The two candidate progenitor bursts for the expanding X-ray rings around AXP 1E 1547.0−5408 occurred at 2009 January 22 6:45:14 UTC and 6:48:04 UTC, with estimated isotropic E_{EM} of 10^{44-45} erg (Tiengo et al. 2010). Table 2 also gives upper limits on the ratio $\gamma \equiv E_{\mathrm{GW}}^{90\%}/E_{\mathrm{EM}}$ for the three bursts with E_{EM} estimates. The γ upper limits for the two ring bursts were estimated using $E_{\mathrm{EM}} = 10^{45}$ erg, and beat the best previous upper limits on γ, set for the SGR 1806−20 giant flare (Abbott et al. 2008b), by a factor of a few.

Superscripts in Table 2 give uncertainties at 90% confidence. The first is a combined statistical and systematic uncertainty in the amplitude of the detector calibrations. The second is a statistical uncertainty arising from using a finite number of injected simulations per upper limit, estimated with the bootstrap method. These uncertainties are added linearly to the final h_{rss} upper limit estimates. Corresponding uncertainties are added to the final E_{GW} upper limit estimates.

The best E_{GW} f-mode upper limits from individual magnetar bursts presented here are an order of magnitude lower (better) than the best f-mode limits from previous searches, and approach the range of EM energies seen in SGR giant flares for the first time. The best SGR 0501+4516 f-mode limit of 1.4×10^{47} erg (at 1090 Hz and a nominal distance of 1 kpc) probes below the 10^{49} erg maximum available energy predicted in Ioka (2001) by two orders of magnitude. The best 100–200 Hz white noise burst limit of 3.5×10^{44} erg is comparable to the E_{EM} seen in giant flares.

A detection of a GW signal from a magnetar would give us a new window through which to probe the stellar physics and structure. However, there are no predictions of the amplitude of GW emission associated with magnetar bursts (although there are constraints on the available energy reservoir e.g. Ioka 2001; Owen 2005; Horowitz & Kadau 2009) and it is unknown at what point in upper limit space we might begin to expect a detection. Improved upper limits and perhaps detection will come in the future via the following routes:

(1) An analysis which stacks isolated bursts (from e.g. SGR 0501+4516 and AXP 1E 1547.0−5408) using the method of Abbott et al. (2009b). Stacking 100 or more bursts observed with a constant detector sensitivity, as in Abbott et al. (2009b), might yield up to an additional order of magnitude improvement in $E_{\mathrm{GW}}^{90\%}$.

(2) The GW detectors will become more sensitive. Second generation detectors (Advanced LIGO and Advanced Virgo) are expected to begin observing by 2015, promising two orders of magnitude improvement in E_{GW} sensitivity over the initial LIGO 4 km detectors (Abbott et al. 2009a). This translates into a $\sim$500x E_{GW} sensitivity improvement over the LIGO 2 km + GEO600 network which observed SGR 0501+4516. Third generation detectors could yield an additional two orders of magnitude in energy sensitivity.

(3) New, nearby magnetars may be discovered in the coming years. The two closest magnetar candidates, SGR 0501+4516 and SGR 0481+5279, were both discovered in the past 2 years; discovery of a source closer to Earth could lead to tighter constraints.

(4) Additional giant flares could push down upper limits on $\gamma \equiv E_{\mathrm{GW}}^{90\%}/E_{\mathrm{EM}}$.

In the meantime, we look forward to further predictions on GW emission amplitudes from these enigmatic sources.

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[98] https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=25737

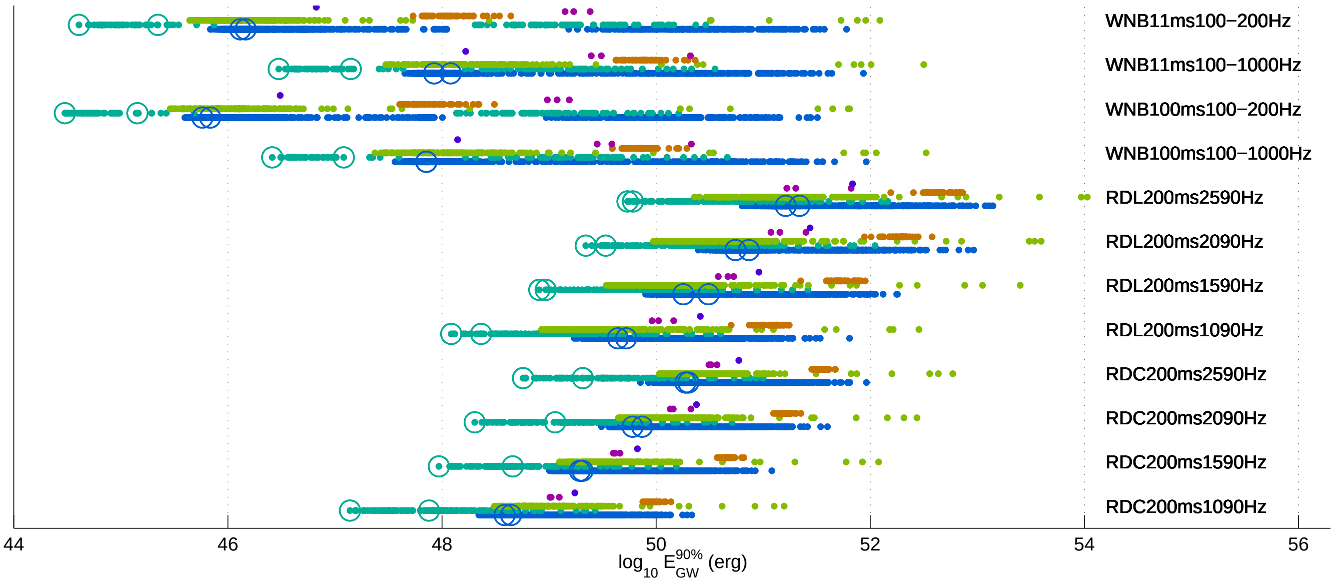

FIG. 3.— $E_{\rm GW}^{90\%}$ upper limits for the entire SGR burst sample for various circularly/linearly polarized ringdowns (RDC/RDL) and white noise burst (WNB) signals (see Section 2). For each of twelve waveform types, we show six rows of dots marking upper limits for the sources (from top to bottom) SGR 1900+14 (violet); SGR 0418+5729 (purple); SGR 1627–41 (orange); SGR 1806−20 (green); SGR 0501+4516 (teal); and AXP 1E 1547.0-4508 (blue) for that waveform type. The limits shown in Table 2 for SGR 0501+4516 and AXP 1E 1547.0-4508 are indicated in the figure by circles.

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TABLE 2

GW strain and energy upper limit estimates at 90% confidence ($h_{\rm rss}^{90\%}$ and $E_{\rm GW}^{90\%}$), for the burst trigger yielding the lowest $E_{\rm GW}^{90\%}$ upper limits (top left), the brightest SGR 0501+4516 burst (top right), and the two 'ring' events from AXP 1E 1547.0−5408 (bottom). Upper limits on the ratio $\gamma \equiv E_{\rm GW}^{90\%}/E_{\rm EM}$ are given when estimates for $E_{\rm EM}$ are available; for the ring events $\gamma = E_{\rm GW}^{90\%}/10^{45}$ erg. Upper limits were estimated using the circularly and linearly polarized ringdowns (RDC/RDL) and white noise burst (WNB) waveforms (see Section 2). Uncertainties, from detector calibration and using a finite number of injected simulations, are added to the final upper limit estimates. These are given for the $h_{\rm rss}$ limits as superscripts, with the first showing detector calibration uncertainty and the second showing statistical uncertainty from finite injected simulations.

	SGR 0501+4516 Best Limits			SGR 0501+4516 Brightest Burst		
Simulation type	$h_{\rm rss}^{90\%}(10^{-22}\ {\rm Hz}^{-\frac{1}{2}})$	$E_{\rm GW}^{90\%}$ (erg)	γ	$h_{\rm rss}^{90\%}(10^{-22}\ {\rm Hz}^{-\frac{1}{2}})$	$E_{\rm GW}^{90\%}$ (erg)	γ
WNB 11ms 100-200 Hz	$7.0^{+1.0\ +0.89} = 8.9$	6.8×10^{44}	-	$13^{+1.9\ +1.3} = 16$	2.2×10^{45}	8×10^{5}
WNB 100ms 100-200 Hz	$5.1^{+0.76\ +0.26} = 6.1$	3.1×10^{44}	-	$11^{+1.6\ +0.69} = 13$	1.4×10^{45}	5×10^{5}
WNB 11ms 100-1000 Hz	$13^{+3.6\ +0.62} = 17$	3.5×10^{46}	-	$25^{+7.3\ +1.6} = 34$	1.4×10^{47}	5×10^{7}
WNB 100ms 100-1000 Hz	$13^{+3.7\ +0.56} = 17$	3.2×10^{46}	-	$26^{+7.3\ +1.4} = 34$	1.2×10^{47}	4×10^{7}
RDC 200ms 1090 Hz	$15^{+2.4\ +1.3} = 18$	1.4×10^{47}	-	$35^{+5.8\ +1.7} = 42$	7.6×10^{47}	3×10^{8}
RDC 200ms 1590 Hz	$30^{+4.9\ +2.1} = 37$	1.2×10^{48}	-	$59^{+9.7\ +2.9} = 71$	4.6×10^{48}	2×10^{9}
RDC 200ms 2090 Hz	$32^{+5.3\ +1.6} = 39$	2.4×10^{48}	-	$69^{+11\ +4.7} = 85$	1.1×10^{49}	4×10^{9}
RDC 200ms 2590 Hz	$40^{+6.7\ +2.9} = 50$	6.1×10^{48}	-	$77^{+13\ +5.2} = 96$	2.1×10^{49}	8×10^{9}
RDL 200ms 1090 Hz	$40^{+6.6\ +8.1} = 54$	1.3×10^{48}	-	$58^{+9.6\ +5.0} = 73$	2.3×10^{48}	9×10^{8}
RDL 200ms 1590 Hz	$86^{+14\ +9.8} = 110$	1.1×10^{49}	-	$80^{+13\ +6.5} = 100$	9.3×10^{48}	3×10^{9}
RDL 200ms 2090 Hz	$96^{+16\ +20} = 130$	2.7×10^{49}	-	$110^{+19\ +12} = 140$	3.4×10^{49}	1×10^{10}
RDL 200ms 2590 Hz	$110^{+19\ +17} = 150$	5.5×10^{49}	-	$120^{+21\ +10} = 160$	6.1×10^{49}	2×10^{10}
	AXP 1E 1547.0−5408 2009 Jan 22 6:45:14 UTC			AXP 1E 1547.0−5408 2009 Jan 22 6:48:04 UTC		
WNB 11ms 100-200 Hz	$7.9^{+1.2\ +1.3} = 10$	1.5×10^{46}	10	$7.6^{+1.1\ +1.0} = 9.8$	1.3×10^{46}	10
WNB 100ms 100-200 Hz	$5.3^{+0.80\ +0.41} = 6.6$	5.8×10^{45}	6	$5.8^{+0.86\ +0.47} = 7.1$	6.8×10^{45}	7
WNB 11ms 100-1000 Hz	$16^{+4.5\ +1.0} = 21$	8.4×10^{47}	8×10^{2}	$18^{+5.2\ +0.91} = 24$	1.2×10^{48}	1×10^{3}
WNB 100ms 100-1000 Hz	$15^{+4.5\ +0.73} = 21$	7.1×10^{47}	7×10^{2}	$16^{+4.5\ +0.80} = 21$	7.2×10^{47}	7×10^{2}
RDC 200ms 1090 Hz	$19^{+3.2\ +1.4} = 24$	3.8×10^{48}	4×10^{3}	$21^{+3.5\ +1.0} = 25$	4.4×10^{48}	4×10^{3}
RDC 200ms 1590 Hz	$30^{+4.9\ +2.5} = 37$	1.9×10^{49}	2×10^{4}	$31^{+5.1\ +1.6} = 37$	2.1×10^{49}	2×10^{4}
RDC 200ms 2090 Hz	$39^{+6.6\ +2.8} = 49$	6.0×10^{49}	6×10^{4}	$44^{+7.4\ +3.8} = 56$	7.4×10^{49}	7×10^{4}
RDC 200ms 2590 Hz	$57^{+9.4\ +3.9} = 70$	1.9×10^{50}	2×10^{5}	$60^{+1.00\ +3.3} = 73$	2.0×10^{50}	2×10^{5}
RDL 200ms 1090 Hz	$60^{+1.00\ +9.9} = 80$	4.4×10^{49}	4×10^{4}	$66^{+11\ +10} = 87$	5.3×10^{49}	5×10^{4}
RDL 200ms 1590 Hz	$84^{+14\ +13} = 110$	1.8×10^{50}	2×10^{5}	$110^{+18\ +22} = 150$	3.1×10^{50}	3×10^{5}
RDL 200ms 2090 Hz	$110^{+19\ +16} = 150$	5.5×10^{50}	6×10^{5}	$130^{+22\ +18} = 170$	7.4×10^{50}	7×10^{5}
RDL 200ms 2590 Hz	$150^{+25\ +33} = 210$	1.6×10^{51}	2×10^{6}	$180^{+30\ +29} = 240$	2.2×10^{51}	2×10^{6}

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