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IMPLICATIONS FOR THE ORIGIN OF GRB 051103 FROM LIGO OBSERVATIONS

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ABSTRACT

We present the results of a LIGO search for gravitational waves (GWs) associated with GRB 051103, a short-duration hard-spectrum gamma-ray burst whose electromagnetically determined sky position is coincident with the spiral galaxy M81, which is 3.6 Mpc from Earth. Possible progenitors for short-hard GRBs include compact object mergers and soft gamma repeater (SGR) giant flares. A merger progenitor would produce a characteristic GW signal that should be detectable at the distance of M81, while GW emission from an SGR is not expected to be detectable at that distance. We found no evidence of a GW signal associated with GRB 051103. Assuming weakly beamed γ-ray emission with a jet semi-angle of 30° we exclude a binary neutron star merger in M81 as the progenitor with a confidence of 98%. Neutron star-black hole mergers are excluded with $> 99\%$ confidence. If the event occurred in M81 our findings support the hypothesis that GRB 051103 was due to an SGR giant flare, making it the most distant extragalactic magnetar observed to date.

Subject headings: gamma-ray bursts – gravitational waves – compact object mergers – soft gamma-ray repeaters

1. INTRODUCTION

GRB 051103 was a short-duration, hard-spectrum gamma-ray burst (GRB) which occurred at 09:25:42 UTC on 3 November 2005 (Hurley et al. 2010) and was possibly located in the nearby galaxy M81, at a distance 3.63±0.14 Mpc from Earth (Golenetskii et al. 2005; Durrell et al. 2010). A preliminary quadrilateral error box obtained by the third interplanetary network of satellites (IPN3) was consistent with a source in the M81 group (Golenetskii et al. 2005). The refined 3-σ error ellipse, shown with a solid black line in Figure 1, has an area of 104 square arcminutes, and excludes the possibility that the GRB's source was the inner disk of M81 (Hurley et al. 2010). The location of the progenitor of GRB 051103 is, however, consistent with the outer disk of M81.

Two other galaxies are noted to lie within the original error box: PGC028505 (distance estimated at 80 Mpc, Lipunov et al. (2005)) and PGC2719634 (distance unknown). PGC2719634 lies on the 18% confidence contour of the refined ellipse and constitutes a plausible host galaxy. PCG028505, however, lies on the 0.03% contour and is unlikely to be the host. Furthermore, PGC028505 was observed in the R and V bands but no evidence for brightening due to an underlying transient source was found (Klose et al. 2005) and it is not thought to be a plausible host of GRB 051103 (Hurley et al. 2010; Lipunov et al. 2005). Observations of the original quadrilateral error box in optical and radio concluded that GRB 051103 was not associated with any typical supernova at $z \lesssim 0.15$ (Ofek et al. 2006). None of the known supernova remnants in M81 fall within the refined elliptical error region.

The progenitors of most short duration GRBs are widely thought to be the coalescence of a neutron star-neutron star (NS-NS) or neutron star-black hole (NS-BH) binary system (see, for example, Nakar 2007 and references therein). With the right combination of binary masses and spins, the neutron star matter is believed to be tidally disrupted leading to the formation of a massive torus. Accretion of matter from this torus onto the final post-merger object leads to the formation of highly relativistic outflows along the axis of total angular momentum of the system (e.g., Setiawan et al. 2004; Shibata & Taniguchi 2006; Rezzolla et al. 2011). Internal shocks in the relativistic jet give rise to the prompt γ-ray

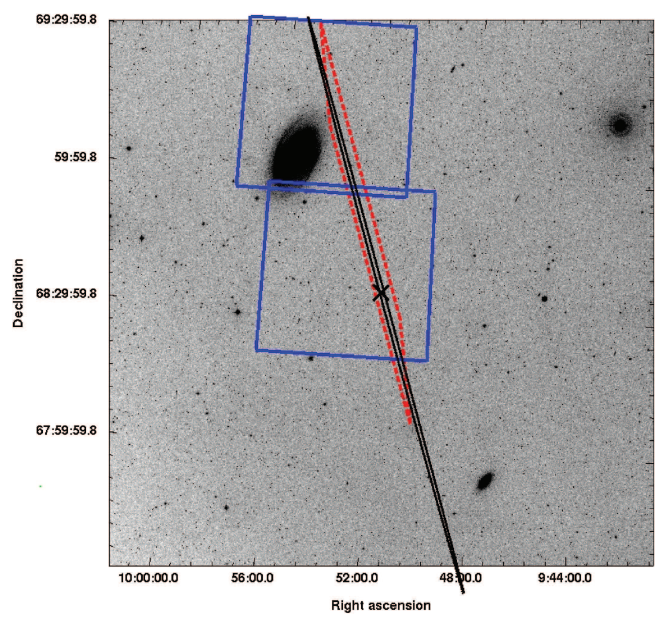

Fig. 1.— The central region of the M81 group, showing the original error trapezium (red dashed line) from the IPN and the refined 3-σ error ellipse (solid black). The blue boxes are the regions studied in the optical. Figure from Hurley et al. (2010) Copyright (c) 2010 RAS.

emission observed in short, hard GRBs.

These binary systems also produce a characteristic gravitational-wave (GW) signal in the last few seconds before coalescence that is detectable by the current generation of interferometric GW detectors, such as those of the Laser Interferometer Gravitational-wave Observatory (LIGO, Abbott et al. 2004, 2009a), to $O(10)$ Mpc. Thus, if M81 was indeed the host of a binary merger progenitor of GRB 051103, LIGO should have detected a GW signal associated with the event. A similar hypothesis was tested for GRB 070201, whose error box overlapped the spiral arms of M31 (which is 770 kpc from Earth). LIGO was able to exclude a compact binary progenitor in M31 at $> 99\%$ confidence (Abbott et al. 2008a) and placed a lower limit of 3.5 Mpc on its distance at 90% confidence.

Up to 15% of short GRBs might be giant flares from soft gamma repeaters (SGRs) in the local universe (Tanvir et al. 2005; Chapman et al. 2009). SGRs are believed to be magnetars; neutron stars with extremely large magnetic fields ($B \sim 10^{15}$ G). However, only a few percent of short GRBs are thought to share the SGR-like properties exhibited by GRB 051103 (Frederiks et al. 2007). For example, the light curve exhibits the steep rise (~ 4 ms) and decaying tail observed in the initial pulses of SGR giant flares (Frederiks et al. 2007; Ofek et al. 2006; Hurley et al. 2010). At the distance of M81 the characteristic late-time weaker, oscillatory phase expected of a SGR giant flare, which follows the rotation of the underlying neutron star, would not be detectable (Hurley et al. 2010). Second, the spectrum of GRB 051103 shows the hard-to-soft evolution characteristic of SGR giant flares (Frederiks et al. 2007). Also, if we assume the source was in M81, the isotropic electromagnetic energy release is approximately 3.6×10^{46} erg (Golenetskii et al. 2005), consistent with the energy release ($\sim 4 \times 10^{46}$ erg) of the SGR 1806−20 giant flare (Hurley et al. 2005). We note that a number of UV-bright regions contained within the elliptical error box indicate star-forming regions in the outer disk of M81 which may host magnetars (Ofek et al. 2006; Hurley et al. 2010). If confirmed, the identification of an SGR in M81 would be the second and most distant extra-galactic SGR flare observed to date.

Several searches for GWs associated with magnetar events have already been performed (Abbott et al. 2007, 2008b, 2009c; Abadie et al. 2011). No evidence of a GW signal was found in these searches, including the 2004 giant flare from the Galactic magnetar SGR 1806−20, which is a factor of ∼300 closer to Earth than M81 (Abbott et al. 2008b). A detectable GW signal from a magnetar giant flare in M81 would therefore probably require $> 10^5$ more energy in the GW emission over SGR 1806−20.

At the time of the GRB, the LIGO detectors were in final preparations for their fifth science run, S5, which began the following day. For this reason, the data from around the time of GRB 051103 has not been included in previous searches associated with GRBs or SGRs in S5 data. Nonetheless, data taken by the LIGO 2 km detector in Hanford, WA (H2) and the LIGO 4 km detector in Livingston, LA (L1) is available. Motivated by interest from the astronomical community and the potential for a GW detection, we have performed a search using the established data analysis pipelines from the S5 searches.

The data was calibrated as described in Abadie et al. (2010a). The validity of the calibration was established by comparing records of the detector configuration at the GRB epoch to those near the start of the science run, and estimates of the calibration uncertainty are accounted for in the GW searches. Data quality studies and techniques for vetoing problematic segments were similar to those used during S5 (Abbott et al. 2009b). These detector characterization studies have established that the data is of science quality and equivalent to that shortly after the official start of S5.

In this paper we report on the LIGO search for GWs associated with GRB 051103, and the resulting implications for the origin of this GRB. Three independent analysis packages, designed for different purposes, were used. In § 2 we describe the method and results of searching for theoretically predicted gravitational waveforms emitted during compact binary mergers. In § 3, we describe the results of two searches using analyses which are designed to be sensitive to unmodelled short-duration ($\lesssim 1$ s) bursts of GWs. The first is an analysis designed to search for GW bursts from magnetar flares. The second performs a search for generic GW bursts from GRBs in the sensitive band of the LIGO instruments. Finally, we summarise our findings in § 4.

2. SEARCH FOR GWS FROM A COMPACT BINARY PROGENITOR

2.1. *Search Method*

The method used to search for the GW signal from binary coalescence is identical to that reported in Abadie et al. (2010b): matched filtering is used to correlate theoretically motivated template waveforms with the data streams from the detectors.

The GW signal from binary coalescence is expected to precede the prompt γ-ray emission by no more than a few seconds. We therefore search for GW signals whose end time lies in an *on-source* window of $[-5, +1)$ s around the reported GRB time. The significance of candidate GW signals is estimated from the background distribution of 324 *off-source* trials, each 6 s long (the number of which is dictated by the quality of the data around the time of the GRB).

The form of the GW signal from compact binary coalescence depends on the masses ($m_{\rm NS}, m_{\rm comp}$) and spins of the neutron star and its companion (either a neutron star or a black hole), as well as the spatial location relative to the detectors, the inclination angle ι between the orbital axis and the line of sight, and the polarization angle specifying the orientation of the orbital axis. The data from each detector is filtered through a discrete bank of template waveforms designed such that the maximum loss of signal-to-noise ratio (SNR) due to discretization effects for a binary with negligible spins is 3%. Although the template bank used ignores spin, we later evaluate our sensitivity to spinning systems and verify that such systems are still detectable. It is assumed that at least one member of the binary is a neutron star with mass $1\,M_\odot \leq m_{\rm NS} \leq 3\,M_\odot$. For the companion object, we test masses in the range $1\,M_\odot \leq m_{\rm comp} \leq 25\,M_\odot$ to allow the possiblity of a either a neutron star-neutron star or neutron star-black hole merger. We note that black hole masses greater than $25\,M_\odot$ seem likely to "swallow" the neutron star whole, without tidally disrupting the neutron star and forming a sufficiently massive accretion disk to power a GRB jet (Belczynski et al. 2008).

If the matched filter SNR exceeds a threshold, the template masses and the time of the maximum SNR are recorded. These *triggers* between detectors are then tested for coincidence in their time and mass parameters (Robinson et al. 2008). This significantly reduces the number of background triggers that arise from matched filtering in each detector independently. Further background suppression is achieved by applying signal consistency tests, specifically a χ^2 test (Allen 2005) and the r^2 veto (Rodriguez 2007). The SNR and χ^2 from a single detector are combined into an effective SNR (Abbott et al. 2008c), which is then summed in quadrature across detectors to form the combined effective SNR which is used as the ranking statistic.

The distribution of effective SNRs can vary significantly across the range of masses being searched, with shorter, higher mass templates more susceptible to non-stationary background noise. Consequently, we split up the search space by mass and re-rank triggers in each mass bin by their likelihood of having arisen due to a gravitational wave signal. This is defined as the efficiency with which we detect plausible gravitational wave signals divided by the false-alarm probability, for a given combined effective SNR. The false-alarm probability is the probability of obtaining a candidate louder than that observed in the on-source trial in the same region of mass space from noise alone; it is measured using the off-source trials. The detection efficiency is computed by adding simulated gravitational wave signals to the data from off-source trials and counting the fraction which are recovered by the detection pipeline.

2.2. *Search Results*

The matched-filter search found no evidence for a GW signal produced by compact binary coalescence at the time of GRB 051103. The most significant candidate event in the on-source region around the time of the GRB had a false alarm probability of 76%. That is, there was a 76% chance of observing a candidate this loud or louder in any given off-source trial due to an accidental coincident noise fluctuation in each detector.

The null-detection result allows us to compute the frequentist confidence with which we may exclude binary coalescence in M81 as the progenitor for this GRB. We used the approach of Feldman & Cousins (1998) to compute regions in distance where GW events would, with a given confidence, have produced results inconsistent with our observations. The Feldman-Cousins confidence regions are computed by analyzing a family of simulated gravitational wave signals, with a choice of priors for the intrinsic parameters motivated by astrophysical observations. Results are quoted explicitly in terms of either a fiducial NS-NS or NS-BH merger.

In the case of NS-NS mergers, masses are drawn from a Gaussian distribution with mean $1.4\,M_\odot$, standard deviation $0.2\,M_\odot$ and truncated at $[1.0, 3.0]\,M_\odot$. The dimensionless spins, $a = Jc/GM^2$, where J is the spin angular momentum and M is the mass, are uniformly distributed within $[0.0, 0.4]$. The upper bound is chosen to be compatible with the spin of the fastest observed millisecond pulsar (Hessels et al. 2006). Our fiducial NS-BH systems have black hole masses drawn from Gaussian with mean $10.0\,M_\odot$, standard deviation $6.0\,M_\odot$ and truncated at $[2.0, 25.0]\,M_\odot$. To reflect the greater uncertainty arising from a lack of observed NS-BH systems, the neutron star mass is drawn from a Gaussian distribution with mean $1.4\,M_\odot$ and standard deviation $0.4\,M_\odot$. Black hole spins are distributed uniformly within $[0.0, 0.98)$. Additionally, population synthesis studies of NS-BH mergers appear to indicate that the tilt angle (the angle between the BH spin direction and the NS orbital axis) must be $< 45°$ in most systems to allow for tidal disruption of the NS and formation of a sufficiently massive torus able to power the gamma-ray burst (Belczynski et al. 2008). Recent numerical simulations of NS-BH mergers lend support to this restriction and find that the tilt angle is likely $< 60°$ (Rantsiou et al. 2008; Foucart et al. 2011). We restrict the tilt angle to be $< 60°$.

The outflows from the accretion jets in a GRB are directed along the rotational axis of the final object. Relativistic beaming and collimation due to the ambient medium confines the jet to a semi-angle $\theta_{\rm jet}$. The observation of prompt γ-ray emission is, therefore, indicative that the inclination of the total angular momentum with respect to the line of sight lies within the jet cone. Estimates of $\theta_{\rm jet}$ are based on jet breaks observed in X-ray afterglows and vary across GRBs. Indeed, many GRBs do not even exhibit a jet break. However, studies of observed jet breaks in Swift GRB X-ray afterglows find a mean (median) value of $\theta_{\rm jet} = 5.4°(6.4°)$, with a tail extending almost to $25°$ (Racusin et al. 2009). In at least one case where no jet break is observed, the inferred lower limit is $25°$ and could be as high as $79°$ (Grupe et al. 2006). In order to probe the range of predicted jet opening angles, we perform separate sets of simulations where the inclination of the total angular momentum is restricted to jet semi-angles of $10°, 20°, \ldots, 60°$ and $90°$, allowing an estimate of exclusion confidence as a function of jet semi-angle.

Systematic errors are treated identically to those in Abadie et al. (2010b): amplitude calibration uncertainty and Monte-Carlo counting statistics from injections are the dominant errors. Amplitude calibration uncertainty is accounted for by multiplying exclusion distances by $1.28\times(1+\delta_{\rm cal})$, where $\delta_{\rm cal}$ is the overall fractional uncertainty in amplitude calibration, estimated at 25%. This is significantly larger than typical science run calibration uncertainties (see e.g., Abadie et al. (2010a)) as fewer calibration measurements were available from this pre-science run time. The factor of 1.28 corresponds to a 90% pessimistic fluctuation, assuming Gaussianity. We incorporate Monte-Carlo uncertainties from the computationally limited number of simulations by stretching the Feldman-Cousins confidence regions to cover a probability interval $\mathrm{CL} + 1.28\sqrt{\mathrm{CL}(1-\mathrm{CL})/n}$, where CL is the desired confidence limit and n is the number of simulations used in constructing the interval.

Figure 2 shows exclusion confidence for NS-NS and NS-BH mergers as a function of jet semi-angle $\theta_{\rm jet}$, assuming a distance to M81 of 3.63 Mpc. If we assume isotropic γ-ray (i.e., unbeamed) emission from GRB 051103 the possibility of NS-NS coalescence in M81 as its progenitor is excluded with 71% confidence. Taking a fiducial

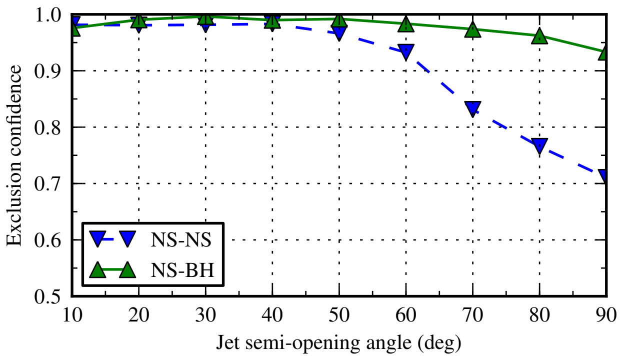

FIG. 2.— Exclusion confidences for the two classes of compact binary coalescences considered in the matched-filter analysis as a function of jet semi-opening angle and assuming a distance of 3.63 Mpc to GRB 051103. The estimate is based on simulations where neutron star masses are Gaussian distributed with mean $1.4\,M_\odot$ and standard deviation $0.2\,M_\odot$. Black hole masses are also Gaussian distributed with mean $10.0\,M_\odot$ and standard deviation $6.0\,M_\odot$. The reduced confidence below 30° is purely due to numerical corrections for limited simulation size.

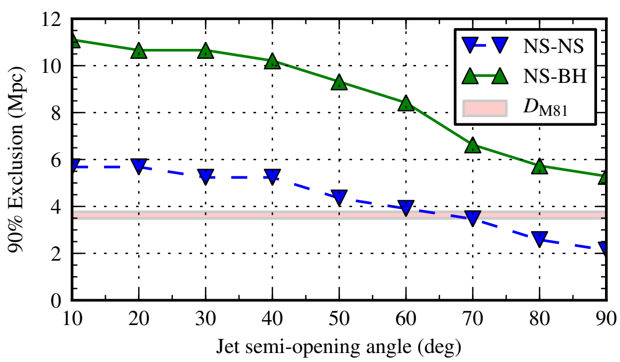

FIG. 3.— 90%-confidence exclusion distance as a function of jet semi-angle for binary coalescences, given LIGO observations at the time of GRB 051103.

jet semi-angle of $\theta_{\rm jet} = 30°$, exclusion confidence rises to 98%. NS-BH mergers with isotropic emission are excluded at 93% confidence, rising to $> 99\%$ for $\theta_{\rm jet} = 30°$.

To address how far we can exclude binary coalescences if GRB 051103 was *not* in M81, figure 3 shows the distance at which we reach 90% exclusion confidence as a function of jet semi-angle. Assuming unbeamed emission, NS-NS mergers are excluded with 90% confidence out to a distance of 2.1 Mpc, rising to 5.2 Mpc for $\theta_{\rm jet} = 30°$. The corresponding distances for NS-BH coalescences are 5.3 Mpc and 10.7 Mpc, respectively.

The increase in exclusion confidence for smaller jet angles is due to the fact that the average amplitude of the GW signal from compact binary coalescence is smaller for systems whose orbital plane is viewed 'edge-on' (where the detector receives the flux from just one GW polarization) than for systems viewed 'face-on' (where the detector receives the flux from both GW polarizations); small jet angles imply a system closer to face-on.

3. SEARCH FOR A GW BURST

3.1. *Search Methods*

We perform two searches for a GW burst associated with GRB 051103. As discussed previously, there is evidence that a fraction of short GRBs are caused by nearby magnetar flares, so we perform a search tailored to the expected GW signal arising from such a flare. Additionally, we perform a search for a generic GW burst in the time around the GRB.

The FLARE pipeline (Kalmus et al. 2007; Kalmus 2008) targets neutron star fundamental mode (f-mode) ringdowns as well as unmodeled short-duration GW signals. It has been used previously to search for GWs associated with Galactic magnetar bursts including the December 2004 giant flare from SGR 1806−20 (Abbott et al. 2008b, 2009c; Abadie et al. 2011). As in the previous magnetar searches, we use an on-source region of $[-2, +2]$ s about the GRB 051103 trigger, and an off-source region of 1000 s on either side of the on-source region to estimate the significance of on-source events.

FLARE produces a time-frequency pixel map from the conditioned and calibrated detector data streams in the Fourier basis, groups pixels using density-based clustering, and sums over the group to produce events. The data from each of the two detectors is combined by including detector noise floor measurements and antenna responses to the source sky location as weighting factors in the detection statistic. 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 where the detectors are most sensitive. In the f-mode band we use a Fourier transform length of 250 ms, which we find to be optimal for f-mode signals expected to decay exponentially with a timescale τ in the 100–300 ms range (Benhar et al. 2004).

The X-PIPELINE analysis package (Sutton et al. 2009) searches for generic GW bursts in data from arbitrary networks of detectors. X-PIPELINE was previously used in the search for GW bursts associated with GRBs in LIGO science run 5 and Virgo science run 1, in 2005–2007 (Abbott et al. 2010). Since the analysis is not based on a specific GW emission model, we keep the search parameters broad to allow for a generic GW burst. In particular, we define our on-source region as the interval $[-120, +60]$ s around the GRB trigger; this conservative window is large enough to accommodate the time delay between a GW signal and the onset of the gamma-ray signal in most GRB progenitor models. We use 1.5 hours of data on either side of the on-source region as the off-source region for background characterization. The frequency band of the X-PIPELINE search is 64–1792 Hz.

X-PIPELINE combines the data streams from each detector with weighting determined by the sensitivity of each detector as a function of frequency and sky position. This yields time-frequency maps of the signal energy in each pixel. Candidate GW events are identified as the loudest 1% of pixels in the map. Each is assigned a significance based on its energy and time-frequency volume, using a χ^2 distribution with two degrees of freedom. These candidates are then refined by comparing the degree of correlation between the H2 and L1 data streams, rejecting low-correlation events as background. Surviving events are ranked by their significance, then each is assigned a false-alarm probability by comparison to events from the off-source region.

3.2. *Search Results*

Neither the Flare magnetar search nor the X-Pipeline analysis yield evidence for a plausible gravitational-wave burst signal associated with GRB 051103. Consequently, we place model-dependent 90% confidence level upper limits on the isotropic energy emission in gravitational waves $E_{\rm GW}$ associated with this GRB.

The limits from the Flare analysis were obtained for twelve types of simulated GW signals: eight f-mode ringdowns with circular and linear polarizations and decay times 200 ms; and four band- and time-limited white noise bursts with durations of 11 ms or 100 ms and spanning the 100–200 Hz and 100–1000 Hz bands. Uncertainties from detector calibrations and Monte Carlo statistics were folded into upper limit estimates as described in Abadie et al. (2011). The best (lowest) upper limit on $E_{\rm GW}$ was 2.0×10^{51} erg, for 100–200 Hz white noise bursts lasting 100 ms. The lowest f-mode upper limit was 1.6×10^{54} erg, for circularly polarized ringdowns at 1090 Hz. These are the lowest frequency signals of each morphology; limits obtained for the other ten simulated signals scale with the noise floor of the LIGO detectors as expected and the simulations provide a check of the robustness of the analysis to the large uncertainty in the frequency of a putative GW signal (for more details on the simulations used see Abadie et al. 2011).

The upper limits produced by the broad X-Pipeline search are computed in a similar way, although they make use of circularly polarized sine-Gaussian waveforms at 150 Hz and 1000 Hz (for details, including handling of uncertainties, see Abbott et al. 2010). We find upper limits on $E_{\rm GW}$ of 1.2×10^{52} erg at 150 Hz and 6.0×10^{54} erg at 1000 Hz. We can convert these results to lower limits on the distance to GRB 051103 as a function of $E_{\rm GW}$, giving 4.4 Mpc $(E_{\rm GW}/0.01 M_\odot c^2)^{1/2}$ at 150 Hz and 0.20 Mpc $(E_{\rm GW}/0.01 M_\odot c^2)^{1/2}$ at 1000 Hz.

Even near the frequency of LIGO's best sensitivity our energy upper limits are several orders of magnitude larger than the maximum energy available for emission by SGRs in gravitational waves $\sim 10^{46}$–10^{49} erg (de Freitas Pacheco 1998; Ioka 2001; Owen 2005; Horvath 2005; Corsi & Owen 2011). Indeed, the energy actually emitted as gravitational waves may be much less than this (Kashiyama & Ioka 2011; Levin & van Hoven 2011). We are therefore unable to inform the hypothesis of an SGR progenitor for GRB 051103.

The sensitivity of the matched-filter search allows us to confidently exclude the hypothesis that the progenitor system was a compact binary merger progenitor in M81. Specifically, assuming an outflow jet semi-angle $\theta_{\rm jet} = 30°$, we exclude a NS-NS merger in M81 at 98% confidence. NS-BH mergers with similarly beamed emission are excluded at $> 99\%$ confidence. Relaxing the assumption of beaming such that we include systems whose orbital plane is oriented edge-on to our line-of-sight, the confidences for NS-NS and NS-BH mergers fall to 71% and 93%, respectively. As a measure of the distance to which we are sensitive to such events, the 90%-confidence exclusion distances for NS-NS and NS-BH systems with beaming are 5.2 Mpc and 10.7 Mpc, respectively. Assuming no beaming, these distances drop to 2.1 Mpc and 5.3 Mpc.

The null result of the searches for an unmodelled burst of GWs allows us to set upper limits on the GW energy emission of GRB 051103. These limits are in the range 10^{51}–10^{55} erg, depending primarily on the assumed GW frequency. These limits are several orders of magnitude greater than the maximum observed electromagnetic emission from SGRs, $\sim 10^{46}$ erg, and the highest predictions of the available resevoir of energy available for gravitational wave emission, so we are not able to constrain the hypothesis of an SGR progenitor for GRB 051103.

We conclude then, that it is highly unlikely that the progenitor for GRB 051103 was a compact binary merger in M81. If the event indeed occurred in M81, it seems likely on the basis of LIGO observations that this was indeed the most distant SGR giant flare observed to date.

4. CONCLUSION

We analyzed data from the LIGO L1 and H2 GW detectors in a frequency band spanning 40 Hz to 3 kHz, looking for a GW signal associated with the short-hard GRB 051103. Three data analysis pipelines were deployed, two of which are designed to search for unmodelled, short-duration ($\lesssim 1$ s) burst-like GW signals and one which performs a matched-filter analysis using templates based on the GW signal expected from compact binary mergers. No evidence was found for a GW signal associated with this GRB.

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