COMPARING $\text{H\alpha}$ AND H1 SURVEYS AS MEANS TO A COMPLETE LOCAL GALAXY CATALOG IN THE ADVANCED LIGO/VIRGO ERA

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ABSTRACT

Identifying the electromagnetic counterparts of gravitational wave (GW) sources detected by upcoming networks of advanced ground-based interferometers will be challenging, due in part to the large number of unrelated astrophysical transients within the $\sim 10–100$ deg$^2$ sky localizations. A potential way to greatly reduce the number of such false positives is to limit detailed follow-up to only those candidates near galaxies within the GW sensitivity range of $\sim 200$ Mpc for binary neutron star mergers. Such a strategy is currently hindered by the fact that galaxy catalogs are grossly incomplete within this volume. Here, we compare two methods for completing the local galaxy catalog: (1) a narrowband $\text{H\alpha}$ imaging survey and (2) an H1 emission line radio survey. Using H$\alpha$ fluxes, stellar masses ($M_*$), and star formation rates (SFRs) from galaxies in the Sloan Digital Sky Survey (SDSS), combined with H1 data from the GALEX Arecibo SDSS Survey and the Herschel Reference Survey, we estimate that an H$\alpha$ survey with a luminosity sensitivity of $L_{\text{H\alpha}} = 10^{40}$ erg s$^{-1}$ at 200 Mpc could achieve a completeness of $f_{\text{SFR}}^\text{H\alpha} \approx 75\%$ with respect to total SFR, but only $f_{\text{SFR}}^\text{H1} \approx 33\%$ with respect to $M_*$ (due to lack of sensitivity to early-type galaxies). These numbers are significantly lower than those achieved by an idealized spectroscopic survey due to the loss of H$\alpha$ flux resulting from resolving out nearby galaxies and the inability to correct for the underlying stellar continuum. An H1 survey with sensitivity similar to the proposed WALLABY survey on ASKAP could achieve $f_{\text{SFR}}^\text{H1} \approx 80\%$ and $f_{\text{SFR}}^\text{H1} \approx 50\%$, somewhat higher than that of the H$\alpha$ survey. Finally, both H$\alpha$ and H1 surveys should achieve $\gtrsim 50\%$ completeness with respect to the host galaxies of short-duration gamma-ray bursts, which may trace the population of binary neutron star mergers.

Key words: galaxies: distances and redshifts – gamma-ray burst: general – gravitational waves – radio lines: galaxies

Online-only material: color figures

1. INTRODUCTION

The inspiral and coalescence of neutron star binaries (NS–NS) are the most likely astrophysical sources for direct detection with the upcoming advanced networks of ground-based gravitational wave (GW) interferometers, such as Advanced LIGO and Virgo (hereafter aLIGO/Virgo; Abramovici et al. 1992; Caron et al. 1999; Acernese et al. 2009; Abadie et al. 2010). Maximizing the science achievable from such detections will require the identification and localization of an associated electromagnetic (EM) counterpart (e.g., Bloom et al. 2009; Phinney 2009; Metzger & Berger 2012, hereafter MB12). The EM–GW link is crucial for identifying the host galaxy and distance of the merger, for placing the mergers in an astrophysical context, for studying the hydrodynamics of matter during the merger process, and potentially for lifting degeneracies associated with the inferred binary parameters (e.g., Hughes & Holz 2003, Nissanke et al. 2010, Kelley et al. 2012).

One commonly discussed EM counterpart of NS–NS mergers is a short-duration gamma-ray burst (GRB); see Fong et al. (2010) and Berger (2011) for evidence favoring this association. Unfortunately, on-axis short GRBs occur at a low rate of $\lesssim 1$ yr$^{-1}$ within the $\sim 200$ Mpc range for NS–NS detections by aLIGO/Virgo (Nakar et al. 2006; Fong et al. 2010; MB12), so the joint detection of a short GRB with a GW event is expected to be rare. More isotropic optical counterparts, such as an off-axis GRB afterglow (Coward et al. 2011; van Eerten & MacFadyen 2011; MB12) or supernova-like emission powered by the decay of radioactive ejecta (“kilonova”; Li & Paczyński 1998; Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Rosswog et al. 2012), may instead represent more promising counterparts for the bulk of GW-detected events (MB12); the typical timescale for these counterparts is a few days. Delayed radio emission, powered by the interaction of (non-)relativistic ejecta with the surrounding environment, may also be detectable if the merger occurs in a sufficiently dense medium, with a timescale of months to decades (Nakar & Piran 2011; Piran et al. 2012).

Regardless of physical origin, a major challenge to identifying EM counterparts is the expected poor sky localizations of $\sim 10–100$ deg$^2$ for networks of GW detectors (Fairhurst 2009; Nisskanne et al. 2011, 2012). In the optical band, this large area will necessitate deep and rapid follow-up with wide-field survey instruments. Still, an even greater challenge may be the large number of false positives in these wide fields (e.g., background supernovae, M dwarf flares, shock break-out events, AGN flares; see Kulkarni & Kasliwal 2009; MB12; Nisskanne et al. 2012). Given the rapid evolution of the predicted optical signal, such false positives need to be quickly eliminated so that candidate counterparts could be followed up with deeper photometry or spectroscopy before the transient fades. Although rapid follow-up is not as essential at radio frequencies, false positives could also be of concern in this case (e.g., radio supernovae, tidal disruption events, AGN flares), given the poorer angular resolution of wide-field radio survey instruments and our lack of knowledge about the transient radio sky on the timescales...
and depths of the expected merger counterparts (e.g., Frail et al. 2012).

The contamination from false positives could be reduced by restricting the search volume to locations near4 galaxies within the sensitivity range of aLIGO/Virgo (z ≲ 0.046; e.g., Abadie et al. 2010). This approach has the potential to reduce the search area from tens of square degrees to ≲0.5 deg², and hence to reduce the number of false positives by a factor of ~10³ (Kulkarni & Kasliwal 2009; Nissanke et al. 2012). However, to successfully implement this strategy, the census of local galaxies must be reasonably accurate and complete. Unfortunately, this is currently not the case: the galaxy catalogs used for recent LIGO/Virgo GW follow-up (Abadie et al. 2012; Evans et al. 2012) are estimated to be only ~60% complete (with respect to B-band luminosity) at 100 Mpc (Kopparapu et al. 2008; White et al. 2011), in which case the true counterpart (most likely at a larger distance) could easily be missed. Furthermore, although B-band completeness is a reasonable proxy for the NS–NS merger population if the latter traces current star formation (e.g., Belczynski et al. 2002), completeness with respect to stellar mass is also relevant if a sizable fraction of mergers occur in early-type galaxies with older stellar populations (e.g., O’Shaughnessy et al. 2008).

In this paper, we compare two approaches for completing the local galaxy catalog. The first strategy is a narrowband Hα survey (Section 2), an idea that has been discussed previously (e.g., Rau et al. 2009; Kasliwal 2012) but is fleshed out in detail here. The other strategy, explored here for the first time, is a wide-field H1 survey (Section 3), as is already being planned as a main science driver for future wide-field radio arrays. Our main conclusion is that neither Hα nor H1 surveys of planned sensitivity are sufficient to fully complete the galaxy catalog, especially with respect to stellar mass. However, even with respect to star formation completeness, an Hα survey suffers from a significant loss of flux (and hence sensitivity and completeness) from spatially resolving the disks of the galaxies and from the effects of Balmer absorption in the underlying stellar continuum. In Section 4, we discuss the merits of combining Hα and H1 surveys, and explore the relevance of our results in the context of the host galaxies of short GRBs (Section 4.1).

2. NARROWBAND Hα IMAGING SURVEY

Most studies in the past have assumed that the rate of NS–NS mergers in the local universe traces B-band luminosity (Phinney 1991; Kopparapu et al. 2008), as would be expected if the rate of mergers is proportional to the current star formation rate (SFR). This naturally led to consideration of narrowband Hα imaging surveys to complete the local galaxy catalog since Hα emission is closely tied to ongoing star formation activity (e.g., Kennicutt 1992; Gallagher & Gibson 1994; Gallego et al. 1995; Kennicutt 1998; Fujita et al. 2003) and imaging surveys can efficiently identify and help characterize galaxies in a given redshift range (Dale et al. 2008, 2010; Ly et al. 2011). In this section, we address the completeness of such a survey as a function of depth in terms of star formation and stellar mass, and discuss the associated challenges.

We first note that while SFR is certainly an important quantity, it is also possible that a sizable fraction of mergers instead trace total stellar mass, as determined by the distribution of merger times and the star formation history (Belczynski et al. 2002, 2006; see Figure 11 of O’Shaughnessy et al. 2008). Leibler & Berger (2010) find evidence from the host galaxies of short GRBs that mergers may track a combination of SFR and stellar mass, in rough analogy with Type Ia SNe (e.g., Scannapieco & Bildsten 2005). Given this possibility, in what follows, we explore completeness with respect to both stellar mass and SFR independently.

In addressing the issue of Hα completeness, we pursue an empirical approach, rather than directly making use of derived relations between Hα luminosity and various galaxy properties. Our primary sources of data are galaxy catalogs with measured Hα fluxes (F_Hα) provided by the MPA-JHU emission line analysis5 from the Sloan Digital Sky Survey (SDSS) Data Release 7 (e.g., Strauss et al. 2002; Abazajian et al. 2009). Each galaxy is characterized by a stellar mass (determined by photometric modeling; Kauffmann et al. 2003; Salim et al. 2007) and SFR (determined from emission lines; Brinchmann et al. 2004). We correct the measured Hα fluxes to account for the finite angular size of the spectroscopic fiber relative to the galaxy by scaling the fluxes by the difference of the total r-band magnitude (keyword r_petro) to that contained in the spectroscopic fiber (keyword r_fiber), as described in Hopkins et al. (2003) and Brinchmann et al. (2004). This assumes uniform Hα surface brightness (see below for further discussion) and allows us to study the completeness achieved by an idealized survey that picks up the entire Hα flux from the galaxy. We also increase the quoted flux errors by a factor of 2.47 (as suggested by the MPA-JHU pipeline) and set a conservative threshold on the signal-to-noise ratio of S/N ≳ 5 for an Hα detection; values with S/N ≲ 5 are treated as upper limits. Finally, we remove all galaxies with “flagged” SFRs (keyword flagSFR = 0) or redshifts (keyword z_warning = 1).

Figure 1 shows our results for the fraction (“completeness”) of the total stellar mass (red) and SFR (blue) within 200 Mpc as a function of the survey flux depth6 (f_Hα,lim) for an idealized spectroscopic survey. Completeness is calculated as the fraction of the total SFR or the total stellar mass in all galaxies with F_Hα ≥ f_Hα,lim normalized to the total SFR or mass of all galaxies in the redshift range z < 0.046. As the flux limit decreases below a few × 10⁻¹⁵ erg s⁻¹ cm⁻², the completeness becomes increasingly uncertain (shown by the hatched uncertainty bands), as increasing fractions of galaxies have only upper limits on F_Hα. The minimum (maximum) completeness in this case is calculated by assuming that none (all) would be detections at F_Hα < f_Hα,lim.

An idealized survey to a depth of f_Hα,lim = 2 × 10⁻¹⁵ erg s⁻¹ cm⁻² (a luminosity of L_Hα,lim = 10⁴⁰ erg s⁻¹ at 200 Mpc), which could be reached with a few minute integration per pointing on a meter-class telescope such as the Palomar Transient Factory (Law et al. 2009), could achieve a completeness of f_Hα ≳ 97% with respect to SFR, but only f_M∗ ≳ 60%–80% with respect to total stellar mass. It is not surprising that f_Hα > f_M∗, given the known correlation between Hα luminosity and SFR (Kennicutt 1998; Kewley et al.

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4 Although it is possible that some mergers will occur far outside of the host galaxy of their stellar progenitors (e.g., Narayan et al. 1992; Kelley et al. 2010), even offsets as large as tens of kpc (as characterize the observed offsets of short GRBs; Berger 2010; Fong et al. 2010) would still reduce the required search area substantially as compared to a search conducted with no information on sky position.

5 http://www.mpq-garching.mpg.de/SDSS/DR7/

6 We do not discuss here whether the Hα survey should be framed as being defined by a flux or equivalent width threshold (e.g., see the discussion in Steidel et al. 2000). This distinction will have a minor effect on our conclusions.
Lower completeness with respect to stellar mass is consistent with the fact that \( \approx 60\% \) of mass in the local universe is in early-type galaxies (Bell et al. 2003), while they account for only \( \approx 10\% \) of the H\( \alpha \) luminosity density at \( z < 0.046 \) (e.g., Nakamura et al. 2003).

For comparison, in Figure 1 we also plot the completeness with respect to \( B \)-Band luminosity using data from the 11HUGS survey of galaxies at \(< 11 \) Mpc (Lee et al. 2007; Kennicutt et al. 2008), and with respect to the total H\( \alpha \) luminosity (using the \( z = 0 \) H\( \alpha \) luminosity function from Gallego et al. 1995; see Ly et al. 2007; Dale et al. 2010). \( B \)-Band completeness (\( f_B^{H\alpha} \)) tracks closer to SFR than to stellar mass, with \( f_B^{H\alpha} \approx 87\% \) completeness at \( L_{H\alpha} = 10^{40} \text{ erg s}^{-1} \). This is not unexpected, as blue light tracks ongoing star formation, although not as tightly as H\( \alpha \) luminosity.

The estimates of mass and SFR completeness in Figure 1 are only appropriate for an idealized survey, such as that realized through direct spectroscopy of the target galaxies (as in SDSS), but with infinite aperture. For an actual imaging survey, absorption in the underlying stellar continuum can reduce the perceived H\( \alpha \) flux when integrated over a filter (e.g., Meurer et al. 2006). While for young star-forming galaxies this will generally be a minor correction (Brinchmann et al. 2004; Meurer et al. 2006), the correction can be significant for early-type galaxies. In Figure 2, we show a comparison between the SDSS spectra of three galaxies with similar H\( \alpha \) fluxes, but where the integrated flux in a narrowband H\( \alpha \) filter is reduced by increasing amounts of Balmer absorption from the stellar continuum. In the bottom spectrum, the H\( \alpha \) equivalent width (EW) is much greater than the correction due to stellar absorption (EW\( _{\text{star}} \)), in which case the galaxy would be detected regardless of the effects of stellar absorption. However, in the top spectrum, EW and EW\( _{\text{star}} \) are comparable, and the galaxy might escape detection in a narrowband imaging survey.

To explore what completeness could be achieved by an actual imaging survey that cannot correct the H\( \alpha \) fluxes for stellar absorption, we recalculated the minimum mass and SFR completeness using the fluxes from SDSS which are instead calculated from the line EWs computed via integration over broad wavelength ranges. The results are shown with dashed lines in Figure 1. Although the effect on SFR completeness \( f_B^{H\alpha} / f_{\text{SFR}} \) is relatively minor (less than a few percent, and comparable to the corrections considered in Meurer et al. 2006), the completeness with respect to stellar mass decreases to \( f_B^{H\alpha} \approx 47\% \). This difference arises because Balmer absorption is strong and H\( \alpha \) is weak in galaxies with relatively old stellar populations and low levels of star formation activity, i.e., those that contribute to stellar mass but not SFR completeness.

Another challenge of a realistic survey is that nearby galaxies generally have angular sizes larger than the typical point-spread-function of a ground-based imaging survey. This effect can reduce the effective survey sensitivity compared to that for point sources (i.e., the survey is actually defined by a limiting surface brightness instead of a limiting flux). The actual correction between limiting surface brightness and limiting flux depends on the background noise level, the typical seeing, and the distribution of galaxy sizes. In Figure 3, we show the distribution of effective angular radii \( (R_{\text{eff}} \equiv R_{\text{ap,SDSS}} \times 10^{r_{\text{fiber}} - r_{\text{petro}}/5}) \) of all galaxies in our sample, where \( R_{\text{ap,SDSS}} \) is the \( 1.5 \) radius spectral aperture of SDSS. A significant number of sources have radii of \( \geq 5'' \), meaning that they will cover \( \geq 10 \) seeing disks for typical conditions, although this will be somewhat mitigated by the fact that H\( \alpha \) typically
fractios. We use the uncorrected SDSS Hα fluxes (i.e., not scaling the Hα fluxes by the total r-band magnitude, as described above). This gives an effective seeing disk of 1.5″, comparable to typical ground-based observing conditions, and basically assumes that the Hα flux outside the central portion is below the detectability threshold. We recompute the stellar mass and SFR completeness using this pessimistic (“imaging”) scenario, and the resulting minimum completeness are shown with solid lines in Figure 1. For a (point source) luminosity of $L_{\text{Hα}} = 10^{40}$ erg s$^{-1}$, the SFR completeness is reduced to $f_{\text{SFR}}^{\text{Hα}} \approx 76\%$, while the stellar mass completeness is $f_{M*}^{\text{Hα}} \approx 33\%$.

In Table 1, we summarize the relevant completeness values. We give three values for the Hα survey, as discussed above. The first corresponds to our ideal survey, where there is no Balmer absorption and all of the flux from extended sources is recovered. The other two (realistic) sets include Balmer absorption, with the optimistic version still assuming that all of the flux from extended sources is recovered, and the pessimistic version assuming that none of the flux from extended sources is recovered; the true value is likely between these last two versions, i.e., $f_{\text{SFR}}^{\text{Hα}} \approx 75\%–95\%$ and $f_{M*}^{\text{Hα}} \approx 30\%–45\%$.

3. H I SURVEY

Another strategy to complete the local galaxy catalog is via a wide-field H I (21 cm) emission line survey, looking for neutral rather than ionized gas. We are motivated in particular by the planned Widefield ASKAP L-band Legacy All-Sky Blind surveY (WALLABY; e.g., Duffy et al. 2012a), which plans to
observe \(\approx 75\%\) of the sky\(^7\) (declination of \(-90^\circ\) to \(+30^\circ\)) over a timescale of \(\approx 1\) year and detect about a half-million galaxies at a distance of 200 Mpc. For this reason, we opt for an empirical approach to estimate the achievable completeness with respect to stellar mass and SFR. We are limited by the absence of a single large sample of galaxies with measured H\(_i\) masses (or upper limits), stellar masses, and SFRs, yet which is unbiased with respect to galaxy population. For this reason, we use several different H\(_i\) catalogs to explore completeness with respect to stellar mass and SFR (see Figure 4 for the H\(_i\) masses and stellar masses).

To study completeness among star-forming galaxies, we use H\(_i\) masses from the Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovannelli et al. 2005) with SDSS counterparts (for which stellar mass and SFR are available as described in Section 2) in the redshift range \(z < 0.046\). Although the entire ALFALFA sample is large (about 9000 galaxies) and covers a wide range in stellar mass (\(M_\star \approx 10^{7.5} - 10^{11.5} M_\odot\)), it is biased toward star-forming galaxies and contains only SDSS counterparts with H\(_i\) detections. A complementary data set is the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010, 2012), which is much smaller (\(\approx 200\) galaxies following our cuts) but also contains deep H\(_i\) upper limits (down to H\(_i\) masses of a few percent of the stellar mass). Unfortunately, even GASS does not represent a fair sample of the entire galaxy population since it is restricted to massive galaxies (\(M_\star \gtrsim 10^{10} M_\odot\)), which, for example, only account for about half of the short GRB hosts (Leibler & Berger 2010); see Figure 4. For this reason, we also use H\(_i\) masses and upper limits from the Herschel Reference Survey (HRS; Cortese et al. 2012), a volume-limited sample at \(< 20\) Mpc (Boselli et al. 2010) that covers a relatively broad range in stellar masses (\(M_\star \approx 10^{8.5} - 10^{11.5} M_\odot\)), covering most of the short GRB host galaxies.

In Figure 5, we show our results for the completeness achievable by an all-sky H\(_i\) survey with respect to total SFR \(f_{\text{SFR}}\) (blue) and stellar mass \(f_{M_\star}\) (red), as a function of survey limiting flux (\(F_{\text{lim}, H_i}\)), calculated using the GASS sample (also see Table 1). For mass completeness, we also show the HRS sample (green). Note that as in the case of H\(_\alpha\) completeness is uncertain at low fluxes as the result of H\(_\alpha\) upper limits, as indicated by the hatched regions.

We find that a survey similar to WALLABY could achieve an SFR completeness of \(f_{\text{SFR}} \approx 93\% - 98\%\), but only \(f_{M_\star} \approx 44\% - 50\%\) with respect to total stellar mass. For mass completeness, we quote numbers from HRS instead of GASS, since HRS

\(^7\) WALLABY may be complemented by similar surveys in the north, such as the proposed Westerbork Northern Sky H\(_i\) Survey; see http://www.astron.nl/~jozsa/wnshs/survey_layout.html.

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Table 1

| Survey Type       | Proposed Depth | \(\text{min}(f_{\text{SFR}})\) | \(\text{min}(f_{M_\star})\) |
|-------------------|----------------|-------------------|-------------------|
| H\(_\alpha\)      | \(2 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) | 97% | 58% |
|                   | \(1 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) | 97% | 59% |
| H\(_\alpha\)      | \(2 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) | 95% | 47% |
|                   | \(1 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) | 96% | 52% |
| H\(_\alpha\)      | \(2 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) | 76% | 33% |
|                   | \(1 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) | 90% | 49% |
| H\(_\alpha\)      | \(0.7\) mJy \times 100 kHz | 93% | 44% |
| H\(_\alpha\)      | \(0.35\) mJy \times 100 kHz | 95% | 49% |

Notes. We give the minimum completeness to SFR and stellar mass based on our strawman H\(_\alpha\) and H\(_\alpha\) surveys. The H\(_\alpha\) flux limit corresponds to a luminosity of \(L_{\text{H\alpha}} = 10^{40}\) erg s\(^{-1}\) at 200 Mpc. The H\(_\alpha\) flux limit corresponds to a luminosity of \(L_{\text{H\alpha}} = 3 \times 10^{41}\) erg s\(^{-1}\), or an H\(_\alpha\) mass of \(M_{\text{H\alpha}} \approx 10^8 M_\odot\).

\(\ast\) This scenario assumes no Balmer absorption and that none of the flux from extended sources is recovered (solid line in Figure 1).

\(\ast\) This scenario includes the effects of Balmer absorption, but assumes that all of the flux from extended sources is recovered (dashed line in Figure 1).

\(\ast\) This scenario assumes the effects of Balmer absorption, but assumes that none of the flux from extended sources is recovered (solid line in Figure 1).

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Figure 4. Stellar mass \(M_\star\) vs. H\(_\alpha\) mass \(M_{\text{H\alpha}}\) from samples of galaxies used in estimating H\(_\alpha\) completeness: ALFALFA (light blue points, detections only); HRS (brown, both detections [squares] and upper limits); and GASS (red, both detections [stars] and upper limits); see the text for references. Vertical blue lines show the masses of short GRB host galaxies from Leibler & Berger (2010), while the horizontal purple line shows the approximate H\(_\alpha\) sensitivity threshold of WALLABY at 200 Mpc. (A color version of this figure is available in the online journal.)
samples a wider range of galaxy masses (Figure 4). Again, a high SFR completeness is expected given the correlation between cold gas mass and SFR (Bigiel et al. 2011). Lower completeness with respect to stellar mass is expected since early-type galaxies are typically deficient in H\(_i\) (Sage et al. 2007; Oosterloo et al. 2010) yet they contain \(\approx 60\%\) of mass in the local universe (Bell et al. 2003). For comparison, we also show completeness with respect to total H\(_i\) mass (as determined from the local H\(_i\) luminosity function of Zwaan et al. 2005), which is found to lie between that of stellar mass and SFR (Figure 5; Table 1).

As we discussed in the context of H\(_\alpha\) surveys, for H\(_i\) surveys, we should also consider the possible detrimental effect of spatially resolving the galaxies. However, the poorer angular resolution of ASKAP (10\(^\prime\)–30\(^\prime\)) makes this less of an issue than for an optical survey, and the expected effect on detectability is anticipated to be minimal (see Figure 5 of Duffy et al. 2012a). The limited angular resolution of the H\(_i\) surveys will not affect the follow-up of GW triggers, as a ±30\(^\prime\) position would be quite sufficient and the H\(_i\) centroid will be known to even better precision. Ideally, candidate galaxies detected by WALLABY will also be followed up to obtain optical counterparts by wide-field survey instruments such as VISTA Hemispheric Survey (Arnaboldi et al. 2007), VST ATLAS (Capaccioli et al. 2005), or SkyMapper (Keller et al. 2007).

4. DISCUSSION

Table 1 compares the minimum completeness to SFR and stellar mass achieved by our fiducial H\(_\alpha\) and H\(_i\) surveys based on Figures 1 and 5. Overall, we find that when considering realistic surveys including the effects of Balmer absorption and finite source sizes, an H\(_i\) survey can achieve a somewhat better completeness in both SFR and \(M_\star\) compared to H\(_\alpha\).

It is clear from our results that neither of the proposed H\(_\alpha\) or H\(_i\) surveys will produce a local galaxy catalog that is entirely complete with respect to stellar mass out to 200 Mpc. Fundamentally, both H\(_\alpha\) and H\(_i\) trace gas, while \(\approx 60\%\) of stellar mass in the local universe is in early-type galaxies (Bell et al. 2003) with little gas. However, even completeness with respect to SFR is unlikely to reach 100\% from either survey due to the issues discussed in Sections 2 and 3.

A remaining question is whether there are any advantages to combining the results of separate H\(_\alpha\) and H\(_i\) surveys. In Figure 6, we show \(L_{H\alpha}\) versus \(M_{H\alpha}\) from the ALFALFA-SDSS sample of star-forming galaxies. We note that an obvious correlation exists between \(M_{H\alpha}\) and \(L_{H\alpha}\) since both trace star formation, but there is also a large scatter (\(\approx 1\) dex) in the correlation where the sensitivity threshold of WALLABY (\(M_{H\alpha}\) \(\approx 10^9\) \(M_\odot\) at 200 Mpc) intersects that of our fiducial H\(_i\) survey (\(L_{H\alpha}\) \(\approx 10^{40}\) erg s\(^{-1}\) at 200 Mpc). This scatter implies that some fraction of galaxies which are just below the detection threshold in H\(_i\) will be detectable in H\(_\alpha\) and vice versa. Therefore, the SFR completeness attained by combining the results of both H\(_\alpha\) and H\(_i\) surveys together should be more than that of either individually.

If one were to combine H\(_i\) and H\(_\alpha\) surveys, which individually achieve a similar completeness (as is the case for WALLABY and our “ideal” spectroscopic H\(_\alpha\) survey),\(^8\) then from the SDSS-ALFALFA sample, we estimate that \(f_{SFR}\) could be increased from \(\sim 95\%\) to \(\sim 98\%\). Mass completeness could be increased by a somewhat greater amount (changing by up to 5); however, the ALFALFA sample includes only H\(_i\) detected galaxies, and hence overestimates the fraction of H\(_i\)-detected galaxies.

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\(^8\) The fact that a smaller fraction of sources lie in the top left quadrant (detected in H\(_\alpha\) but not H\(_i\)) of Figure 6 than in the bottom right (detected in H\(_i\) but not H\(_\alpha\)) appears to be at odds with the comparable completeness attained by our fiducial H\(_i\) and spectroscopic H\(_\alpha\) surveys (see Figures 1 and 5); however, the ALFALFA sample includes only H\(_i\) detected galaxies.
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≈10%–20%), however, \( f_M \) is ultimately limited to a value \( \lesssim 60\% \) due to the fraction of early-type galaxies which possess neither detectable H\( \alpha \) nor H\( \alpha \) emission. We conclude that combining surveys provides the greatest benefit if both H\( \alpha \) and H\( \alpha \) surveys separately achieve a similar completeness, however, even in this case, the gains will be relatively modest.

4.1. Connection to Short GRB Hosts

So far, we have focused on completeness with respect to SFR and stellar mass separately. However, it is also of interest to investigate how complete the H\( \alpha \) or H\( \alpha \) surveys will be with respect to the known population of short GRB host galaxies. We attempt to answer this question empirically by investigating the fraction of galaxies with properties (SFR or stellar mass \( M_\star \)) similar to those of the short GRB hosts that would be detected in H\( \alpha \) or H\( \alpha \).

In our calculation, we use short GRB host galaxy masses from Leibler & Berger (2010) and SFRs (or upper limits) from Berger (2009), resulting in a sample of 11 galaxies. We define the “short GRB host completeness” as the fraction of galaxies in our sample that have masses (and in some cases SFRs) within a factor of ±0.5 dex of those of each short GRB host and that are detectable at a given H\( \alpha \) or H\( \alpha \) flux, the result of which is then averaged over the short GRB hosts. In the case of H\( \alpha \), the galaxy masses, SFRs, and H\( \alpha \) fluxes are again taken from the SDSS sample (Section 2), the latter of which are not corrected for stellar absorption or galaxy size (as would characterize a purely imaging survey). In the case of H\( \alpha \), we use galaxy masses from the HRS sample, but we cannot make a cut on the SFR since these data are not available.

Figure 7 shows our results for completeness as a function of H\( \alpha \) or H\( \alpha \) flux, normalized to the sensitivity of our fiducial surveys. In the case of H\( \alpha \), results are shown for two cases: (1) in which the galaxy samples are chosen to match both the masses and SFRs of the short GRB hosts, and (2) in a case for which the samples are chosen based just on sharing similar stellar masses with the short GRB hosts. By this criteria, we find that our fiducial H\( \alpha \) imaging survey could achieve a short GRB host completeness of \( f_{H\alpha}^{SGRB} \approx 50\% \) and \( \approx 25\% \) in cases (1) and (2), respectively. Case (1) is more realistic and results in a higher completeness because most of the short GRB hosts (9 of 11) are star-forming galaxies, so the SFR cut preferentially picks out H\( \alpha \)-luminous galaxies. In both cases, the minimum completeness asymptotes to \( \approx 80\% \) at low fluxes since 2 of 11 of the short GRB hosts are early-type galaxies, for which there are only upper limits on their SFRs and H\( \alpha \) luminosities.

In the case of H\( \alpha \), we find that our fiducial survey, similar to WALLABY, could achieve a completeness of \( f_{H\alpha}^{SGRB} \approx 45\% \). However, this probably underestimates the true completeness for the same reason as with H\( \alpha \): most short GRB hosts are star forming and there is a correlation between SFR and H\( \alpha \) mass (Bigiel et al. 2011), yet no cut was made on SFR.

We conclude that both H\( \alpha \) and H\( \alpha \) surveys could achieve at least \( \sim 50\% \) completeness with respect to GRB host galaxies, although this number is likely to be substantially higher in the case of an H\( \alpha \) survey. There is room to increase the completeness by performing a deeper search than our fiducial survey.
potentially approaching the $\sim 80\%$ maximum completeness expected if one could detect all 9 of the 11 star-forming short GRB hosts at $\sim 200$ Mpc.

5. CONCLUSIONS

We used observed samples of nearby galaxies, drawn from SDSS and augmented by H I data from several surveys, to estimate the completeness of fiducial H$\alpha$ and H I surveys to SFR and stellar mass out to a distance of 200 Mpc. We conclude that neither H I nor H$\alpha$ surveys to proposed depths will be entirely effective at completing the local galaxy catalog with respect to stellar mass within 200 Mpc, but that we can expect reasonable completenesses of $f_{H\alpha}^{\text{SFR}} \approx 76\%$, $f_{M_*}^{\text{SFR}} \approx 33\%$, $f_{H\alpha}^{\text{M}_*} \approx 93\%$, and $f_{M_*}^{\text{H I}} \approx 44\%$. At this point, neither the large-scale H$\alpha$ nor H I surveys discussed here are underway, and it may be possible to alter the strategy (i.e., survey depth) to increase the completeness. For instance, halving the survey threshold of the fiducial H$\alpha$ imaging survey results in a substantial increase in the completenesses to $f_{H\alpha}^{\text{SFR}} \approx 90\%$, $f_{M_*}^{H\alpha} \approx 49\%$, but for H I only results in a modest increase to $f_{H\alpha}^{\text{M}_*} \approx 95\%$, and $f_{M_*}^{\text{H I}} \approx 50\%$. For H$\alpha$, these increases are comparable to that achieved by pursuing a spectroscopic survey (Figure 1). Such a deeper survey would also increase the completeness with respect to short GRB host galaxies by $\gtrsim 10\%$ (Figure 7). Also note that the nominal $z \lesssim 0.046/200$ Mpc range on which we have focused is just an estimate of the average distance to a merger detected by aLIGO/Virgo for an assumed set of parameters (array configuration, search strategy, detection threshold, etc.). However, some mergers could be detected out to the larger distances (e.g., 400 Mpc), and the addition of future more sensitive interferometer arrays (e.g., the Einstein Telescope) could push this horizon substantially further. An H$\alpha$ survey would require additional dedicated filters to push its redshift coverage beyond $z = 0.046$, and so its redshift coverage would need to be determined carefully in advance (separately from any sensitivity considerations). In contrast, the WALLABY survey plans to cover redshifts out to 0.26, so increases in the horizon are easily accommodated.

If the survey thresholds remain as discussed here, then assessing whether or not this is a concern for aLIGO/Virgo follow-up largely depends on the fraction of mergers that occur in early-type galaxies. If the host galaxies of short GRBs indeed represent a faithful sampling of the merger population, then the current census of about a five to one ratio of star forming to elliptical hosts (Berger 2011) would suggest that incompleteness of early-type galaxies is not a major concern. On the other hand, it is also possible that short GRBs do not represent all mergers, or that the short GRB host population is biased against early-type galaxies. Current population synthesis models do allow for a sizable fraction $\gtrsim 20\%$–50\% of elliptical hosts at $z = 0$ (O’Shaughnessy et al. 2008).

We note that our treatment of the surveys used simply defined empirical data sets, and some secondary effects may change the results slightly. For instance, neither the H$\alpha$ flux nor the Balmer absorption is expected to be distributed uniformly within
focused on Hα galaxy properties to directly calculate the completeness. As a final consideration, we note that although we have focused on Hα and H i surveys, wide-field broad-band optical or infrared photometric surveys such as the Large Synoptic Survey Telescope (LSST; e.g., Strauss et al. 2010), Pan-STARRS (Kaiser et al. 2002), VISTA Hemispheric Survey (Arnaboldi et al. 2007), VST ATLAS (Capaccioli et al. 2005), or SkyMapper (Keller et al. 2007) may also be useful in assembling a local galaxy census for aLIGO/Virgo follow-up. Photometric surveys provide only approximate redshifts, and hence the resulting list of potential host galaxies for a given gravitational wave detection will be inaccurate to some degree; however, such detailed redshift information is otherwise not essential to planning follow-up searches. One benefit of photometric surveys is that they are less biased toward star formation and hence will pick up a larger portion of the local stellar mass. A drawback of photometric surveys is the potential that a particularly inaccurate redshift could result in follow-up searches completely missing the true host galaxy. Photometric surveys may thus represent a promising complement to Hα and H i surveys, the merits of which will be studied in greater detail in future work.

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