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Search for Electromagnetic Counterparts to LIGO-Virgo Candidates: Expanded Very Large Array† Observations

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Abstract. This paper summarizes a search for radio-wavelength counterparts to candidate gravitational-wave events. The identification of an electromagnetic counterpart could provide a more complete understanding of a gravitational-wave event, including such characteristics as the location and the nature of the progenitor. We used the Expanded Very Large Array (EVLA) to search six galaxies which were identified as potential hosts for two candidate gravitational-wave events. We summarize our procedures and discuss preliminary results.

Keywords. Gravitational waves, methods: observational, radio continuum: general

1. Gravitational-Wave Astronomy and the Time Domain

Gravitational waves (GWs) are fluctutions in the space-time metric, equivalent to electromagnetic waves resulting from fluctuations in an electromagnetic field. Because of the weakness of the gravitational force, however, a laboratory demonstration of GWs comparable to Hertz's demonstration of electromagnetic waves is not possible. Indeed, the characteristic scale for the luminosity of a GW source is $L_0 = 2{\times}10^5\ M_\odot\ c^2\ \mathrm{s}^{-1}$, indicating immediately that the generation of GWs will occur in astrophysical environments in which large masses are moving at high velocities.

Precise timing of pulses from the radio pulsar PSR B1913+16, which is one member of a double neutron star system, has already revealed indirect evidence for GWs (Hulse & Taylor 1975; Weisberg *et al.* 2010). In this system, the rate of orbital-period decay as predicted by general relativity is consistent with that observed from the pulsar timing measurements. Since the discovery of that system, other pulsars in neutron star–neutron star binaries have also been discovered, and the predicted levels of orbital-period decay from general relativity remains consistent with those from the measurements.

From the standpoint of time-domain astronomy, many of the other predicted sources of GWs are rapidly time-varying phenomena. They include the mergers of compact objects (neutron star–neutron star, neutron star–black hole and black hole–black hole mergers), asymmetric supernovae, rapidly rotating asymmetric neutron stars, and exotic objects such as oscillating cosmic strings.

While evidence for GWs remains indirect, the promise of direct detection of GWs has excited considerable international interest. In Europe, the AstroNet *A Science Vision*

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for European Astronmy posed "Can we observe strong gravity in action?" as a key question for this decade, while in the U.S., gravitational-wave astronomy was identified as a scientific frontier discovery area in the *New Worlds, New Horizons in Astronomy and Astrophysics* Decadal Survey. In this respect, GW astronomy is similar to the experience in opening up new spectral windows in the electromagnetic spectrum. As each new spectral window has been opened, entirely new classes of sources have been discovered. Indeed, one of the most surprising results of GW astronomy would be if *no* new classes of sources were discovered as this new window on the Universe is opened.

2. Electromagnetic Counterparts to Gravitational Wave Events

Supernovæ have a well-known electromagnetic signature, and asymmetric supernovæ are predicted to be gravitational wave emitters. It is therefore natural to anticipate that other gravitational-wave emitters might also display electromagnetic counterparts. Moreover, the identification of electromagnetic counterparts to GW events would have a number of benefits:

- Precise localization of the event, potentially at the sub-arcsecond level, is possible via electromagnetic observations. Such localization may be crucial in understanding the nature of the event (for instance, whether in the nucleus of a galaxy or in its outskirts).
- The characteristics of the electromagnetic counterpart, such as its spectrum, are likely to constrain the environment or progenitor, or both, of the GW event.

In many respects, determining the electromagnetic counterpart to a GW event is analogous to determining the (electromagnetic) spectrum of a transient discovered in one band and then following up at others (e.g., a gamma-ray burst discovered at gamma-ray wavelengths and then followed up at X-ray, optical and radio wavelengths).

Our focus on radio-wavelength counterparts is motivated by several considerations:

- Non-thermal, high-energy particles often produce radio emission easily, particularly in the presence of a magnetic field (e.g. cyclotron and synchrotron emission).
- Radio observations can yield precise astrometry, in the best cases obtaining positions at the milliarcsecond level.
- Radio wavelengths are unaffected by dust obscuration, either from the immediate environment of the event or from intervening objects.
- Radio telescopes can observe during the day, offering rapid follow-up.
- If a GW event also produces a radio burst or pulse, the propagation of this pulse will be delayed by its propagation through the ionized interstellar (and intergalactic) medium. Such delays can be minutes to hours, depending upon the electron column density along the line of sight, but they potentially allow for detailed follow-up of the burst.

3. LIGO-Virgo Observations

The radio-wavelength observations that we describe below are based on coordinated observations between the Laser Interferometric Gravitational-wave Observatory (LIGO) and the Virgo that occurred during the Autumn of 2010 (LIGO Scientific Consortium & Virgo Collaboration 2011). LIGO has two elements, one located in Hanford, WA, USA, and the other in Livingston, LA, USA, while Virgo has one element located near Pisa, Italy. Together they form a 3-element interferometer.

The LIGO-Virgo interferometer measures differences of arrival times. Analyses of test waveforms injected into the LIGO-Virgo processing pipeline indicate that a candidate's position can be localized only to a region of order 10 deg^2. Ordinarily, such a large uncertainty region could not be useful in searches for a radio counterpart with the current generation of telescopes, because their fields of view are too small. However, the most likely sources that the LIGO-Virgo interferometer could detect at reasonable signal-to-noise ratios would have occurred within 40 Mpc. If one assumes that a candidate event is associated with a galaxy, then the typical number of galaxies within the certainty region of a GW candidate is only three. This small number of galaxies can be usefully searched.

4. Expanded Very Large Array Observations

The Expanded Very Large Array (EVLA) is a 27-element radio interferometer operating between 1 and 50 GHz. It has been the focus of a recent major upgrade (which is nearly complete), and it is being commissioned with science programmes that are now well established. For the purpose of these observations, the EVLA offers a number of attractive features:

• The wide frequency (wavelength) coverage potentially allows "tuning" of the observations to a frequency well matched to the expected physics. In this case, we observed at 5 GHz (λ6cm), at which both expanding synchrotron fireballs and relativistic jets are likely to be detectable.

• At our observational frequency, the nominal field of view (approximately $7'$) is well matched to the size of most local galaxies. In practice, the field of view is usually defined as the region over which the antenna response is at least half its peak value; sources outside the nominal field of view can still be detected, provided that they are sufficiently strong to compensate for the decreased antenna response. Accordingly, in order not to miss a potential candidate, we imaged a much larger region—typically $30'$.

• The angular resolution of the EVLA can be adjusted by moving the individual elements. During most of our observations the angular resolution achieved was about $4''$, which provides about $0\farcs4$ localization (equivalent to 20 pc at 10 Mpc) for a reasonable signal-to-noise ratio.

We have now conducted three epochs of observations for each of the two LIGO-Virgo candidates, observing all of the nearby galaxies within the uncertainty region. Fig. 1 (left) shows the field around one of the galaxies; Fig. 1 (right) displays the flux curves of the detected sources. Typically we detected $\sim$6 sources in the field of each galaxy. That small number of sources is consistent with the number of extragalactic sources expected (Windhorst 2003), but does not exclude the possibility that one of the radio sources is a counterpart to the LIGO-Virgo candidate.

Data acquisition and reduction of all three epochs for both candidates has only recently been concluded. In assessing the reality of any potential radio-wavelength counterpart to either LIGO-Virgo candidate, other potential sources of variability must also be considered. On the time-scales and cadence of our observations, it is unlikely that intrinsic variability of any active galactic nuclei (AGN) in the field of view would represent a source of contamination. However, at these wavelengths, refractive interstellar scintillation due to the Galaxy's interstellar medium is a potential source of contamination (for instance, an AGN unrelated to the LIGO-Virgo candidate might show variability on the time-scales of our observations).

5. Future

LIGO and Virgo are currently being upgraded. When that is completed ($\sim$2014) they will be more sensitive and able to probe to larger distances. We expect a much larger number of galaxies to be identified as hosts, and as a search of all of them with the EVLA

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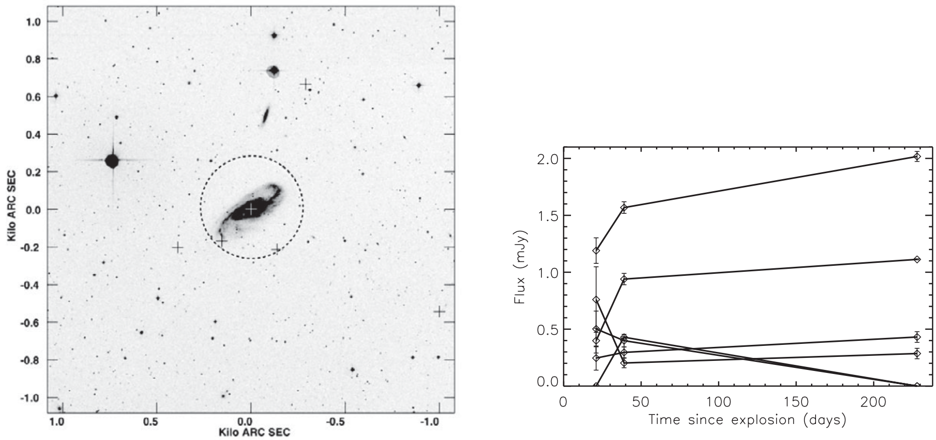

Figure 1. Left: Radio wavelength (λ6cm) sources detected in the field of view of one of the galaxies representing a potential host of a candidate LIGO-Virgo gravitational-wave event. Plusses represent the detected sources, and the circle represents the approximate "field of view," defined as the half-power point of the antenna response. Right: Radio flux curves for those sources.

would then be very time consuming (see also Metzger & Berger 2011), a change in observing strategy will be needed. An approach similar to current follow-ups of supernovae could be profitable: if an optical counterpart is found, the EVLA could used to assess the radio-wavelength properties of the counterpart.

Later in the decade other radio-wavelength facilities are likely to be available, thus presenting additional opportunities. Among them are (1) the Low Frequency Array (LOFAR), which could conduct wide-field "blind" searches at metre wavelengths (30–240 MHz) for northern-hemisphere counterparts, (2) the Karoo Array Telescope (MeerKAT), which could conduct southern-hemisphere follow-up observations similar to those of the EVLA, and (3) the Australian Square Kilometre Array Pathfinder (ASKAP), which could conduct wide-field "blind" searches at decimetre wavelengths ($\sim$ 1 GHz) for southern-hemisphere counterparts.

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