Fast Radio Bursts with Apertif

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6.13 Discussion

6.13.1 Prospects for counterpart identification

While for some FRBs we have already identified one or more galaxies in their localisation regions, there are probably more, too faint to be included in the GLADE catalogue. Here we estimate the total number of galaxies we might expect in the localisation regions of our FRBs.

The number of potential host galaxies in a localisation region depends strongly on which types of galaxies are considered to possibly host FRB progenitors: Dwarf galaxies are far more common than massive galaxies. As the first repeating source, FRB 121102, was localised to a dwarf galaxy with a high specific Star Formation Rate (SFR; Tendulkar et al. 2017), it was thought that this type of galaxy might be related to the FRB progenitor type. However, other FRBs — both repeating and non-repeating — have now been localised to a variety of galaxies (Chatterjee et al. 2017; Bannister et al. 2019; Ravi 2019; Prochaska et al. 2019; Marcote et al. 2020). We here apply the same analysis as done for FRB 110124 (See Chapter 3 and references therein) and estimate the number of dwarf galaxies \(4 \times 10^7 M_\odot < M_{\text{stellar}} < 10^{10} M_\odot\), i.e. at least as massive as the host galaxy of FRB 121102) and massive galaxies \(M_{\text{stellar}} > 10^{11} M_\odot\) in the FRB localisation volumes. From the mass functions of Baldry et al. (2012) and Haynes et al. (2011), we estimate a dwarf galaxy number density of \(n = (0.02 - 0.06) \text{ Mpc}^{-3}\). For massive galaxies we use the luminosity function of Faber et al. (2007), and find \(n = (1.5 - 2.0) \times 10^{-3} \text{ Mpc}^{-3}\).

The expected number of galaxies in an FRB localisation region is the galaxy number density multiplied by the comoving volume out to the redshift of the FRB, assuming that the mass functions do not evolve significantly up to the maximum redshift \(z \approx 1\) of our FRB sample. The redshift is estimated from the IGM DM contribution \((\text{DM}_{\text{IGM}})\) using Eq. 6.10. \(\text{DM}_{\text{IGM}}\) can be related to other sources of DM as

\[
\text{DM}_{\text{IGM}} = \text{DM} - \text{DM}_{\text{MW}} - \text{DM}_{\text{halo}} - \frac{\text{DM}_{\text{host}}}{1 + z},
\]

where \(\text{DM}_{\text{MW}}, \text{DM}_{\text{halo}},\) and \(\text{DM}_{\text{host}}\) are the DM contributions from the Milky Way, its halo, and the host galaxy (which includes the environment local to the source), respectively. For the Milky Way contribution, we take the lowest value predicted by the NE2001 and YMW16 models (see Table 6.1). Based on the Yamasaki & Totani (2019) model, we conservatively assume 10 pc cm\(^{-3}\) from the Milky Way halo, and we set the host galaxy contribution to zero. The resulting redshift estimates are conservative upper limits.

In Fig. 6.27 we show the resulting number of expected galaxies as a function of comoving volume. The comoving volume upper limit associated with each FRB is calculated as the total comoving volume to the FRB’s redshift multiplied by the fraction of the sky covered by the localisation region. The number of expected dwarf galaxies is \(\geq 1\) for all our FRBs, up to several hundred for FRB 190925. If a localisation region contains a known dwarf galaxy, one thus cannot straightforwardly conclude it is the host. Other, potentially unknown, dwarf galaxies will also most likely be present. In contrast, the number of expected massive galaxies is less than one for four of our FRBs. For the FRB with the smallest comoving volume
associated with its localisation region, FRB 200216, the expected number is \( \sim 0.20 \). Assuming Poissonian error bars, the probability of finding a massive galaxy in the region by chance is then 18%. It would therefore also not be possible to definitively associate a massive galaxy with any of our FRBs.

In order to rule out spatial coincidence at the 95% level, we find that the comoving volume should be limited to \( \sim 30 \text{ Mpc}^3 \) for association with a massive galaxy, and \( \sim 2 \text{ Mpc}^3 \) for association with a dwarf galaxy. Such volumes could be reached by either better FRB localisation, or by finding an FRB at a relatively small distance. For example, an FRB with the same localisation region as our best-localised burst, FRB 200216, but at redshift of \( z = 0.27 \), as opposed to the current upper limit of \( z = 0.45 \) (see Table 6.1), would be localised to the required comoving volume to rule out spatial coincidence with a massive galaxy. For a dwarf galaxy association, the redshift upper limit is \( z = 0.11 \). Such redshifts are not unreasonable within the overall FRB population: For example, the FRB presented in Chapter 3, FRB 110214, has a redshift upper limit of \( z = 0.14 \).

In the future, ARTS FRB localisation may be improved in two ways: First, an FRB may be observed to repeat with ARTS. Each additional burst will lead to another localisation ellipse, which when combined would then lead to a region that could be as small as \( 10'' \times 10'' \). Second, ALERT connects ARTS with LOFAR. An FRB that is detected by ARTS could be observed by the TBBs of LOFAR (see Chapter 4). If FRBs emit at LOFAR frequencies, we can localise these to a square arcsecond. With such localisation accuracy, host galaxy association becomes feasible out to much larger redshifts.

Another potentially interesting avenue is to look for a persistent radio source counterpart, as was discovered for FRB 121102 (Chatterjee et al. 2017; Marcote et al. 2017). The only other localised repeating FRB, R3, does not have a persistent radio source down to a deeper luminosity limit than the luminosity of the counterpart of FRB 121102 (Marcote et al. 2020). In fact, a persistent radio source has not been found for any other FRB thus far. As already discussed in Sect. 6.8.2.1, radio point sources are sparser than optical galaxies, hence ARTS localisation regions might be small enough to identify radio sources associated with our FRBs.

For each FRB, we set a lower limit to the flux density of a persistent radio source that is ruled out to be in the localisation region by chance at the 10% level following Eftekharí et al. (2018). The resulting flux densities are listed in Table 6.2. Given the current 5\( \sigma \) sensitivity limit of the Apertif imaging surveys of 350 \( \mu \text{Jy} \) (see Fig. 6.16), we note that Apertif imaging could identify persistent radio sources that are unlikely to be in the localisation region by chance for the majority of our FRB sample. WSRT thus has not only the capability to discover FRBs, but to identify potential persistent radio sources associated with them as well.

### 6.13.2 Probing the M33 halo

As shown in Fig. 6.28, three of our first four detections and one unverified FRB candidate were found in the angular vicinity of Local Group galaxy M33 (the Triangulum galaxy). This is because our first detection, FRB 190709, was discovered during a calibration drift scan.
6.13 Discussion

Figure 6.27: The expected number of galaxies in the FRB localisation areas for a range of dwarf galaxy (dark blue) and massive galaxy (cyan) number densities as function of comoving volume. The comoving volume depends on both the redshift of the FRB and the size of the localisation region on-sky, and should be regarded as an upper limit. The horizontal line indicates where the expected number of galaxies is one.

Table 6.2: Flux densities above which no persistent radio sources are expected to be found in the FRB localisation region by chance at the 10% level. Apertif imaging can, at a current 5σ sensitivity limit of 350 µJy, reach these limits for most sources.

<table>
<thead>
<tr>
<th>FRB</th>
<th>S (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190709</td>
<td>2.1</td>
</tr>
<tr>
<td>190903</td>
<td>5.4</td>
</tr>
<tr>
<td>190925</td>
<td>5.3</td>
</tr>
<tr>
<td>191020</td>
<td>5.4</td>
</tr>
<tr>
<td>191108</td>
<td>0.14</td>
</tr>
<tr>
<td>191109</td>
<td>0.34</td>
</tr>
<tr>
<td>200210</td>
<td>2.2</td>
</tr>
<tr>
<td>200213</td>
<td>0.031</td>
</tr>
<tr>
<td>200216</td>
<td>0.14</td>
</tr>
</tbody>
</table>
observation of the quasar 3C48, which is in the Triangulum constellation. FRB 190925 and FRB 191108 were later detected during follow-up observations of our first discovery. While FRB 191108 has the lowest angular separation from the core of M33 and has the smallest localisation region, all three sources are well within the Galactic halo of both M33 and the much larger M31 (Andromeda) galaxy. All of their DMs ought to have some component that is attributable to the shared plasma between M33 and M31, and that amount can be no larger than the minimum extragalactic DM of the three FRBs. Given that the lowest extragalactic DM of the three is \( \sim 540 \text{ pc cm}^{-3} \), which is an order of magnitude larger than the expected contribution from the Local Group plasma, we are not able to significantly constrain the electron column density in the CGM of M33 and M31. However, with a larger sample of FRBs from Apertif and other surveys, a floor on the DM in that direction could be established or even a spatial DM gradient in the direction of M31 could emerge. None of the three bursts show evidence of temporal scattering. As described further in Sect. 6.8.4.2, FRB 191108 shows some frequency structure, but the broad, \( \sim 40 \text{ MHz} \) fluctuations are likely not due to propagation effects in the M33 Galactic halo.

### 6.13.3 All-sky burst rate

With ALERT we have discovered nine FRBs in a total of 1100 observing hours, corresponding to one FRB every \( \sim 5.3 \text{ days} \). To convert this to an all-sky rate, we calculate the Apertif FoV out to half-power from our CB model. This results in a FoV of 8.2 sq. deg. at 1370 MHz. We note that the FoV of a single CB is \( \sim 0.3 \text{ sq. deg.} \) at 1370 MHz, so Apertif increased the WSRT FoV by a factor \( \sim 30 \). At higher frequencies, the relative FoV increase is even higher. Using a Poissonian 95% confidence interval (Gehrels 1986), the inferred all-sky rate is \( 960^{+860}_{-520} \text{ bursts sky}^{-1} \text{ day}^{-1} \).

This burst rate is valid above a given fluence completeness threshold. To calculate this for Apertif, we consider the SEFD of the system, which is typically 85 Jy (Chapter 4). However, this value is measured for the centres of the CBs and varies across the FoV as is clearly visible in Fig. 6.1. The most conservative completeness threshold could be derived using twice this SEFD as we take our FoV to be the FoV out to half-power. However, most FRBs will be found in a part of the FoV that is more sensitive. Therefore we consider this limit too conservative: In 85% of the FoV, the sensitivity is at least 70% of the maximum value. Instead of 50%, we take this 70% of peak sensitivity as our sensitivity threshold. Using the radiometer equation (Eq. 6.8), we then find a fluence completeness threshold of \( 1.6\sqrt{\frac{W}{\text{ms}}} \text{ Jy ms} \).

The derived burst rate is in agreement with earlier values at 1400 MHz from surveys with similar fluence thresholds (Champion et al. 2016; Bhandari et al. 2018; Rane et al. 2016).

### 6.14 Conclusions

We have reported the detection of nine FRBs using Apertif. By combining multibeam and interferometric information, we were able to localise the FRBs to narrow ellipses. Four are in the direction of Local Group galaxy M33. One of those is bright, highly Faraday rotated,
Figure 6.28: The location of the four FRBs that cut within 50 kpc of M33.
and has an impact parameter with M33 of just 18 kpc, roughly the diameter of that galaxy's disk. Its RM of $+474 \pm 3$ rad m$^{-2}$ is one of the largest of any published value and is an order of magnitude larger than the expected contribution from the Milky Way, the IGM, and the halos of M33 and M31. The most plausible location of the magnetised plasma is therefore a dense region near the FRB-emitting source itself. Preliminary results indicate that one of the FRBs might have an RM of $−1988$ rad m$^{-2}$, which if confirmed may bridge the gap between the RMs of one-off FRBs and the very high RM of FRB 121102. These results demonstrate that Apertif can localise one-off FRBs with an accuracy that maps magneto-ionic material along well-defined lines of sight. Our rate of 1 every $\sim 5$ days next ensures a considerable number of new sources are detected for such studies. Together, these nine FRBs thus mark a new phase in which a growing number of bursts can be used to probe our Universe.

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