Fast Radio Bursts with Apertif

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6.8  FRB 191108

FRB 191108 was detected in three CBs, across a total of 48 SBs. The discovery DM was 588 pc cm$^{-3}$. Fig. 6.13 shows the dynamic spectrum of the dispersed pulse as well as the dedispersed pulse profile. The maximum S/N from the real-time detection was 60 and our machine learning classifier assigned a probability of $>99.9\%$ of it being a real transient (Connor & van Leeuwen 2018). The real-time detection triggered a dump of the full-Stokes data (Sect. 4.5.4.3), allowing us to analyse the polarisation properties of the burst.

6.8.1  Polarisation properties

FRB 191108 was measured to be roughly 50% linearly polarised and $\leq 13\%$ circularly polarised (Fig. 6.14). It was found to have a rotation measure (RM) of $+474\pm3$ rad m$^{-2}$. The best-fit RM was obtained by applying a linear least squares fit to position angle (PA) as a function of wavelength squared. The sign was determined by verifying that the Crab pulsar had an RM of $-43$ rad m$^{-2}$ during an observation the same day.
Figure 6.12: The localisation region of FRB 191020. The CBs at 1370 MHz are shown in white (non-detection) and green (detection). The red, elongated and very narrow area indicates the 90% confidence level localisation area. The localisation is not constrained towards lower declinations.

Figure 6.13: The dispersed dynamic spectrum of FRB 191108 across the ARTS observing bandwidth, and the dedispersed and frequency-averaged pulse profile for 30 ms of data (inset). The dynamic spectrum has been bandpass corrected and median subtracted, but not RFI cleaned. It is has been binned down to 0.82 ms time resolution with 0.78 MHz frequency channels.
Both bandpass calibration and polarisation calibration were done using 3C286, a standard calibrator source, which is known to have very little circular polarisation. We treat the Stokes-V value as an upper limit because of uncertainty in the polarisation calibration procedure. 3C286 was observed in the same CB as the FRB, but it was observed in the central TAB, where leakage is expected to be lowest. FRB 191108 was found in SB 37, which is a linear combination of non-central TABs. That SB may have slightly different leakage properties than the central TAB, which will be better quantified as the system is further calibrated. From the 3C286 on/off observation, we solved for a single phase in each down-channelised frequency channel, knowing that the complex XY correlation ought to be purely real if Stokes V is zero. We verified that the polarisation calibration solution agreed with a different method that used the FRB itself, which separated the component of \( \text{Im} \{ XY' \} \) that varies with \( \lambda^2 \) from that which does not, since Stokes V should not exhibit Faraday rotation under most circumstances. Fortunately, the polarisation rotation does not vary with parallactic angle on Westerbork data, since the dishes are on equatorial mounts. Thus, differences in hour angle between the two observations have no influence. Still, it is possible that the calibration solution is sufficiently different between TABs and SBS that the observed 13% circular polarisation is spurious. Fortunately, Faraday rotation is robust against uncertainty in the polarisation calibration solution, because it is difficult to mimic a rotation in the Q/U-plane that is sinusoidal in \( \lambda^2 \). We are thus confident in the reported value of the RM.

We see no evidence of a swing in the PA across the pulse. FRB 121102 was also found to have a flat PA (Michilli et al. 2018; Gajjar et al. 2018; Hessels et al. 2019), as was FRB 180916.J0158+65 (known as R3; CHIME/FRB Collaboration et al. 2019c). This is in contrast to many pulsars, and it may have interesting implications for FRB emission mechanisms. In our case, however, the flat PA may be instrumental. While the true PA could be flat across the pulse like for previous FRBs, the intrinsic width of FRB 191108 is temporally unresolved, meaning any swing in the polarisation PA is unobservable: The apparent flat PA across the pulse is the time-averaged angle of the true pulse. This can lead to depolarisation, because coarse temporal sampling and intra-channel dispersion effectively add linear-polarisation vectors across the pulse that may point in different directions. The depolarisation fraction is

\[
    f_{\text{depol}}(\Delta \theta) = 1 - \cos\left(\frac{\Delta \theta}{2}\right).
\]

Here, \( \Delta \theta \) is the PA change across the pulse in radians. Since we observe \( \sim 50\% \) of the FRB emission to be linearly polarised, the true pulse must be at least as polarised and its \( \Delta \theta \) cannot be greater than \( \sim 120^\circ \). It is possible that FRB 191108 and other temporally-smeared FRBs with moderate polarisation fractions have higher intrinsic polarisations than inferred.

### 6.8.2 Localisation of FRB 191108

FRB 191108 was detected in CBs 15, 21, and 22, across a total of 48 SBS. The final derived 90% confidence localisation region is shown in Fig. 6.15. This source is well-localised, owing to its high S/N and resulting detection in many SBS. The best-fit position (J2000) corresponds to RA=01:33:47, Dec=+31:51:30. The error ellipse has a semi-major axis of 3.5' and a semi-minor axis of 2.5'', with a position angle of 19.5° East of North. The FRB is localised to a region
Figure 6.14: The measured polarisation properties of FRB 191108. The top panel shows the frequency-averaged pulse profiles after correcting for Faraday rotation in total intensity, \(I\), linear polarisation, \(L\), and circular polarisation, \(V\). The middle panel shows a flat PA across the pulse, which could be intrinsic or due to depolarisation, as the true FRB width is temporally unresolved. The bottom panel shows the bandpass-corrected frequency spectrum, as well as the Faraday-rotated Stokes \(Q\) and \(U\). The best fit RM is \(+474\pm3\) rad m\(^{-2}\).
1.20 ± 0.05° from the core of Local Group galaxy M33. The GLADE catalogue lists one known galaxy within the redshift upper limit of \( z < 0.52 \) (see Sect. 6.8.4.1) located at \( \sim 45'' \) from the localisation ellipse. However, the localisation solid angle of approximately 2100 sq. arcsec (90% confidence) is too large to unambiguously identify a host galaxy associated with the FRB, even if the DM/\( z \) relation is to be trusted and utilised (Eftekhari & Berger 2017). If, as we discuss in Sect. 6.8.6, FRB 191108 is found to repeat and is detected at a different parallactic angle, we will achieve \( \sim \) arcsecond localisation in both directions, because the TABs will be at a different position angle on the sky.

![Figure 6.15: The localisation region of FRB 191108. The compound beams at 1370 MHz are shown in white (non-detection) and green (detection). The red, elongated and very narrow area around the cross indicates the 90% confidence level localisation area. The galaxy near the bottom of the figure is M33, which is 1.20 ± 0.05° from the location of the FRB. Background image from the Sloan Digital Sky Survey (SDSS; York et al. 2000).](image)

6.8.2.1 Apertif continuum survey & radio counterpart

We have searched for a persistent radio source associated with FRB 191108 in continuum images from the Apertif imaging surveys (Hess et al. 2020\(^1\)). The mosaic in Fig. 6.16 is a combination of 31 CBs from two survey pointings (191010042 and 191209026) which overlap around the localisation region. The continuum images for the mosaic were made using the top 150 MHz of the Apertif imaging band (1280–1430 MHz). The mosaic covers \( \sim 9 \) deg\(^2\) and M33 can be seen in the bottom half of the map. We did not find anything within the localisation error region above 5\( \sigma \) at 71 \( \mu \)Jy root-mean-square noise.

\(^1\) https://alta.astron.nl
Figure 6.16: A mosaic from the Apertif imaging surveys combining 31 compound beams from two adjacent pointings around the localisation region. The mosaic has a synthesised beam of $31.6'' \times 31.6''$. In the FRB localisation region, marked by the white ellipse, no persistent radio counterpart brighter than $\sim 350 \mu$Jy ($5\sigma$ limit) was found.
Radio point sources have a lower on-sky density than faint optical galaxies, which decreases the probability of chance spatial coincidence and relaxes the localisation requirements for radio counterparts (Eftekhari et al. 2018). The persistent radio source associated with FRB 121102 was roughly 200 µJy at \( z \approx 0.2 \) at 1 GHz (Chatterjee et al. 2017), meaning we could have detected an equivalent nebula above 3\( \sigma \) if FRB 191108 were at the same distance as FRB 121102. This is closer than the maximum redshift implied by the extragalactic DM of FRB 191108, which is \( z \approx 0.52 \) (see Sect. 6.8.4.1). Therefore, the host-galaxy Inter-Stellar Medium (ISM) or the dense magnetised plasma contributing to the RM of the FRB would need to contribute a significant amount of DM in order for us to detect a persistent source similar to the one associated with FRB 121102. This is not implausible: Using the same Galactic halo modelling and DM/\( z \) relation employed in this chapter (Eq. 6.10), the extragalactic DM of FRB 121102 implies a redshift that is 60% larger than the known value of its host galaxy. The Galactic centre magnetar, PSR J1745–2900, is both strongly Faraday rotated (\( \text{RM} \approx 7 \times 10^4 \text{ rad m}^{-2} \)) and dispersed (\( \text{DM} \approx 1780 \text{ pc cm}^{-3} \)) near to the source, which would make it seem very distant if it were bright enough to be seen by an extragalactic observer (Eatough et al. 2013). Nonetheless, we note that of the five unambiguously localised FRBs, no source has a host-galaxy DM that is known to be significantly more than half its extragalactic DM (Tendulkar et al. 2017; Bannister et al. 2019; Prochaska & Zheng 2019; Ravi et al. 2019; Marcote et al. 2020).

If there were a radio source associated with M33 at 840 kpc, we can set an upper limit on its luminosity of \( \nu L_\nu < 8.5 \times 10^{31} \text{ erg s}^{-1} \). At 1400 MHz, many supernova remnants (Chomiuk 2010) and HII regions (Paladini et al. 2009) would have been detectable if they were at the same distance as M33. M33 is known to have RGB stars stretching \( \sim 2^\circ \) north of the core, nearly three times the radius of the classical disk (McConnachie et al. 2009, 2010), due to past interactions with M31. The northern part of M33 also has many HII regions (Relaño et al. 2013), but most are within 10 kpc of the core (30 arcminutes below FRB 191108). Therefore, even though it is plausible that there would be stellar structure or star formation at the location of FRB 191108, we do not find evidence for a strong Faraday rotating plasma associated with M33. These facts, along with the arguments presented in Sect. 6.8.5, suggest the FRB’s RM arises in its host galaxy.

### 6.8.3 Time & frequency structure

We do not find evidence of temporal scattering in FRB 191108. Even though visually there appears to be slightly more power after the main peak of the FRB pulse profile than before it, the detected pulse width is consistent with intra-channel dispersion smearing and the sampling time of our instrument. We have also fit pulse width as a function of frequency and found the data to prefer dispersion smearing over scattering. The latter would result in a \( \tau \propto \nu^{-4} \) relationship for a single-screen, whereas instrumental smearing between channels causes the width to scale as \( \nu^{-3} \), assuming dispersion smearing is larger than sampling time. We find the best-fit \( \tau(\nu) \) power-law to be \(-2.9\), implying that the pulse is temporally unresolved even at 275 µs. We also compared our pulse with simulation codes simpulse\(^1\) and

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\(^1\) https://github.com/kmsmith137/simpulse
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injectfrb\(^1\), which generate realistically smeared FRBs and account for finite channelisation and temporal sampling. We simulated bursts with the same DM but varying intrinsic widths, assuming the same time and frequency resolution as ARTS, and fit their 'observed' widths with the same pipeline that was used for the FRB. We found that the intrinsic width of FRB 191108, and any scatter-broadening, must be \(\lesssim 80\) \(\mu\)s.

In the top panel of Fig. 6.14, there is excess power after the primary pulse, and between 17 and 19 ms the PA appears non-random and consistent with the PA of the main pulse. Indeed, when the primary pulse is masked out, we find a 7.5\(\sigma\) pulse with a best-fit width of 1 ms. Such a broader, weaker subpulse after the bright, narrow main pulse has been seen in other FRBs, for example the repeating FRB 180916.J0158+65 (see pulse d in Fig. 1 from Marcote et al. 2020) as well as the first repeater, FRB 121102 (see pulse a in Fig. 1 from Michilli et al. 2018).

As argued by Connor (2019), the observed widths of many FRBs are close to the instrumental smearing timescale, i.e. \(\sim \sqrt{\tau_{\text{DM}}^2 + \tau_{\text{samp}}^2}\), indicating that there may exist large numbers of narrow bursts that are missed by current search backends. When FRBs are coherently dedispersed or observed with high time/frequency resolution, structure is often revealed on timescales of tens of microseconds (Ravi et al. 2016; Farah et al. 2018; Hessels et al. 2019). FRB 191108 may therefore be an example of this population of narrow FRBs that are often missed without high time and frequency resolution backends — something Apertif does have.

A least-squares power-law fit was applied to the Stokes I frequency spectrum of the FRB, yielding a power-law index of \(-1.6 \pm 0.5\). But like other FRBs, FRB 191108 is not well described by a power law. In the centre and top of the band there is a factor of \(~2\) of excess power (see the bottom panel of Fig. 6.14). Our constraint on the scatter-broadening implies a lower limit on the de-correlation bandwidth originating from Galactic scintillation of a few kHz. However, as argued in Section 6.8.4.2, the observed frequency modulation, with characteristic bandwidth of the order of 40 MHz, is unlikely to be due to scintillation. Such bandedness has been seen in more extreme cases by ASKAP (Shannon et al. 2018) and CHIME (CHIME/FRB Collaboration et al. 2019b), as well as in FRB 121102 (Hessels et al. 2019; Gourdji et al. 2019). It may prove to be a generic property of FRB spectra. On the other hand, narrow burst emission from only a few Galactic neutron stars has been observed to show such bandedness which cannot be explained due to scintillation (Hankins et al. 2016; Pearlman et al. 2018; Maan et al. 2019).

6.8.4 M33 and M31 halos

The sky location of FRB 191108 is spatially separated by 1.20 \(\pm 0.05^\circ\) and 13.90 \(\pm 0.04^\circ\) from Local Group galaxies M33 and M31, respectively. As M33 is located at a distance of 840 kpc from the Milky Way, this translates to an impact parameter of 18 kpc to the M33 core. M31 is approximately 770 kpc away, meaning FRB 191108 came within roughly 185 kpc of Andromeda. Since they are relatively nearby, the CircumGalactic Medium (CGM) around

\(^1\)https://github.com/liamconnor/injectfrb
the two galaxies, as well as the baryonic bridge between them, subtend a large angular size. We therefore expect the FRB to have travelled through the CGM of both galaxies. Below we consider how these media might have contributed detectable propagation effects to the pulse signature of FRB 191108.

6.8.4.1 Local Group DM contribution

Prochaska & Zheng (2019) model the CGM of M31, which is large enough to engulf the CGM of M33, as it extends \( \sim 30^\circ \). They use a modified Navarro–Frenk–White (NFW) profile and assume \( M_{\text{halo}}^{\text{M31}} \approx 1.5 \times 10^{12} \, M_\odot \) and \( M_{\text{halo}}^{\text{M33}} \approx 5 \times 10^{11} \, M_\odot \). Prochaska & Zheng also consider a ‘Local Group Medium (LGM)’, which models the total intra-group plasma. Using Fig. 9 in that paper, FRB 191108 would have an additional \( \sim 40–60 \, \text{pc cm}^{-3} \) imparted by the halos of M33 and M31.

The hot gas in the Milky Way halo is also expected to contribute to the DMs of extragalactic objects. Prochaska & Zheng (2019) estimate a typical contribution of 50–80 \( \, \text{pc cm}^{-3} \). Yamasaki & Totani (2019) use recent diffuse X-ray observations to model the halo DM, and account for the apparent directional dependence of emission measure (EM). The authors include a hot disk-like halo component as well as the standard spherically symmetric halo to calculate \( DM_{\text{halo}} \) as a function of Galactic longitude and latitude. Using their analytic prescription, we estimate the Milky Way halo contribution to be \( 30 \pm 20 \, \text{pc cm}^{-3} \) in the direction of FRB 191108. Keating & Pen (2020) find a broader range of allowed values for the Galactic halo DM contribution than previous studies, but also favour smaller values. Combining the estimates of DM from the Milky Way ISM and halo, along with the plasma surrounding M33 and M31, the DM of FRB 191108 beyond the Local Group could be \( 380–480 \, \text{pc cm}^{-3} \).

Using the approximate DM/redshift relation from Petroff et al. (2019a),

\[
DM \approx 930 \, z \, \text{pc cm}^{-3}, \tag{6.10}
\]

and subtracting the expected Milky Way and Local Group DM contribution, the implied redshift upper limit on the source is \( z \approx 0.52 \).

ASKAP has also found an FRB that appears to pass through an intervening halo, coming within \( \sim 30 \, \text{kpc} \) of a massive foreground galaxy (Prochaska et al. 2019). This allowed the authors to place constraints on the net magnetization and turbulence in the foreground galaxy halo, due to the relatively low RM and dearth of scattering in FRB 181112. In our case, the high RM of FRB 191108 does not set a strong upper-limit on the halo magnetic field along the line of sight. Instead we suggest using the large number of polarised extragalactic objects behind M31 and M33 to constrain their CGM (see Fig. 6.17).

6.8.4.2 CGM scattering & scintillation

Recently, quasar absorption spectroscopy has been used to constrain CGM gas (Prochaska et al. 2014). Contrary to simple physical models of virialisation in massive dark matter halos, the absorption studies have found that most quasars that pass within \( \sim 150 \, \text{kpc} \) of a foreground
galaxy indicate the existence of cool ($10^4$ K) gas embedded in a hot ($10^6$ K) CGM. It has been argued that gas in these environments is prone to fragmentation, leading to a ‘cloudlet’ model of the CGM in which sub-parsec cold gas clumps are distributed throughout the hot background medium (McCourt et al. 2018). Vedantham & Phinney (2019) investigated whether or not this cloudlet model of the CGM could impact FRBs.

The lensed geometric time delay is maximised when the foreground galaxy is halfway between the observer and the source. Given that M33 is at a distance of just 840 kpc and the FRB emitting source is likely much farther away, we do not expect detectable temporal scattering from the intervening halo. Instead, we might expect to see frequency scintillation. NE2001 predicts a Galactic scintillation bandwidth of $\approx 1.8$ MHz in the FRB direction (Cordes & Lazio 2002), which is expected to occur if the FRB has not been significantly scatter broadened before entering the Galaxy. We compute the auto-correlation function of the FRB frequency spectrum and fit it with a Lorentzian function (Lorimer & Kramer 2005), finding a de-correlation bandwidth of $\Delta \nu \sim 40$ MHz, shown in Fig. 6.18. This appears to be dominated by the patches of increased brightness around 1370 MHz and 1500 MHz, which are approximately as wide as the best-fit de-correlation bandwidth. This is an order of magnitude larger than the expected Galactic scintillation bandwidth in the FRB direction and is consistent with the banded frequency structure of other FRBs.

To search for Galactic scintillation, we tried removing frequency modulation on scales above 20 MHz by subtracting a tenth-order polynomial fit from the data, allowing us to look for correlations at smaller $\Delta \nu$. We found positive correlation below a few MHz at the level of 5%, which is lower in amplitude than FRB 110523 (Masui et al. 2015), but roughly the same as the auto-correlation function found for FRB 180916.J0158+65 (Marcote et al. 2020). All are consistent with the de-correlation bandwidth from Galactic scintillation predicted by NE2001 for their respective frequencies and directions.
If the $\Delta \nu \sim 40$ MHz frequency modulation were scintillation originating in the halo of M33, angular broadening would cause the FRB to no longer be a point source for Galactic scattering screens and we should not see correlations at $1$–$2$ MHz scales. The angular broadening can be determined by noting $\tau \approx 1/2\pi \Delta \nu = 4$ ns. Assuming the FRB is emitted from a much greater distance than M33, the broadening is given by (Thompson et al. 2017),

$$\theta \approx \sqrt{\frac{2c\tau}{d_{\text{M33}}}} \approx 2 \mu\text{arcsecond.} \quad (6.11)$$

If the origin of the frequency modulation of FRB 191108 is indeed interference from a scattering screen near M33 and not intrinsic to the source, Galactic scintillation would be quenched. Scintillation tends to only occur for sources smaller than 0.1 arcseconds at 1 GHz, because extragalactic sources will not scintillate if their angular size is significantly greater than the Fresnel scale of the scattering screen in the Milky Way (Dennett-Thorpe & de Bruyn 2002). This is why so few quasars scintillate in the ISM but pulsars do, and why stars scintillate in our atmosphere but the planets do not. These arguments against the frequency modulations originating in scintillation near the M33 halo are in line with other FRBs, which often show banded structure over 10s or 100s of MHz.
6.8.5 Rotation measure origin

The observed RM of an FRB can be broken down into several components between the observer and source,

$$\text{RM}_{\text{obs}} = \text{RM}_{\text{MW}} + \text{RM} + \text{RM}_{\text{host}}, \quad (6.12)$$

where $\text{RM}_{\text{MW}}$ is the foreground RM from the Milky Way, RM is from the intergalactic medium, and $\text{RM}_{\text{host}}$ comes from the host galaxy ISM and the region near the FRB progenitor. In the case of FRB 191108, we might also include $\text{RM}_{\text{LG}}$, the contribution from the Local Group. This is the contribution of the galactic halos of M33 (Triangulum) and M31 (Andromeda), and the broader shared plasma linking the two nearby galaxies with the Milky Way. The expected Milky Way foreground is $\text{RM}_{\text{MW}} \approx -50 \text{ rad m}^{-2}$ (Oppermann et al. 2015). Fig. 6.17 provides an idea of the spatial scatter of this value. Our observed $\text{RM}_{\text{obs}} = +474 \pm 3 \text{ rad m}^{-2}$ thus translates to an estimated extragalactic contribution of approximately 525 rad m$^{-2}$.

Such a large extragalactic RM is not expected from the InterGalactic Medium (IGM), as it would require ordered $\mu$G magnetic fields over gigaparsec scales to achieve $10^{2-3} \text{ rad m}^{-2}$ for typical FRB redshifts. No intergalactic magnetic fields have been detected, but they are expected to be roughly nG in strength (Michilli et al. 2018).

We consider the possibility that the ionised material surrounding M33/M31 could contribute all the required magnetised plasma to account for the RM of the FRB, but do not find this compelling: By taking the catalogue of 41632 extragalactic RMs from Oppermann et al. (2012), we identify 93 objects that pass within $5^\circ$ of M33, roughly the angular radius of the expected 75 kpc halo. 93% of these sources have RMs between $-15$ and $-90 \text{ rad m}^{-2}$ — probably dominated by the Milky Way foreground like most polarised extragalactic sources — and none is larger in magnitude than 100 rad m$^{-2}$. In Fig. 6.17 we plot the distribution of extragalactic RMs near the Local Group on the sky to demonstrate the extent to which FRB 191108 is an outlier. Therefore, unless the source has a very unusual sight-line and travels through a dense magneto-ionic region in the M33/M31 halo with the opposite magnetic field sign, the absence of strong Faraday rotation in other extragalactic polarised sources behind M33 suggests the FRB RM is imparted elsewhere. The dataset plotted in Fig. 6.17 could still be a useful probe of CGM magnetic fields in its own right: The black points in the left panel that have a low impact parameter with M31 show a small gradient such that their amplitude increases towards smaller angular separations. Whether this is due to structure in the Galactic foreground Faraday field or in the M31 halo could be teased out with a Galactic DM map.

Given that we do not expect the large RM of the FRB to be dominated by either the Milky Way, M33, or the IGM, it is likely that the magnetised plasma is in the host galaxy. Using the estimated maximum redshift implied by the extragalactic DM, of $z \approx 0.52$, and noting that the local RM will be a factor of $(1+z)^2$ larger than the observed RM due to cosmological redshift, $\text{RM}_{\text{host}}$ could be of order $10^3 \text{ rad m}^{-2}$. Even if the host galaxy contributes significantly to the extragalactic DM and the FRB is much closer than the redshift implied by Eq. 6.10, the RM would still be much larger than that expected from the ISM of a Milky Way-like galaxy, unless observed very close to edge-on.
FRBs are now known to be located in a range of environments spanning different galaxy types. While there exist examples of polarised FRBs without significant Faraday Rotation (Ravi et al. 2016; Petroff et al. 2017), several sources appear to pass through regions of highly-magnetised plasma. The first was FRB 110523, which was detected with the Green Bank Telescope. It had an RM of \(-186\) rad m\(^{-2}\). Like the Apertif-discovered FRB 191108, this is larger than expected from the Milky Way and the IGM (Masui et al. 2015). The authors argued that its high RM and scattering properties suggested a dense magnetised environment local to the source. The FRB with the highest published DM, FRB 160102, had an RM of \(-220\) rad m\(^{-2}\) (Caleb et al. 2018); its local RM could be as large as \(-2400\) rad m\(^{-2}\) if a significant portion of the DM comes from the IGM. During Breakthrough Listen observations on the Parkes telescope, FRB 180301 was detected and full-polarisation data was preserved (Price et al. 2019). They report an RM of \(-3163 \pm 20\) rad m\(^{-2}\), although the patchiness of their frequency spectrum causes the authors to question their Faraday rotation fit. CHIME has found a repeating FRB whose RM exceeds the Galactic foreground by two orders of magnitude, with RM \(-499.8 \pm 0.7\) rad m\(^{-2}\) (Fonseca et al. 2020). Finally, FRB 121102 has an RM of \(10^5\) rad m\(^{-2}\) and is spatially coincident with a bright, compact radio source (Michilli et al. 2018). This is larger than even the Galactic centre magnetar, PSR J1745–2900, with RM \(7 \times 10^4\) rad m\(^{-2}\) (Eatough et al. 2013). Both FRB 121102 and PSR J1745–2900 have been seen to exhibit significant RM variation over month to year timescales (Desvignes et al. 2018).

The analogy between FRB 121102 and the Galactic centre magnetar may extend beyond just phenomenological similarities. If the persistent radio source coincident with FRB 121102 is similar to a low-luminosity active galactic nucleus, then that system may be another example of a circumnuclear magnetar, a scenario that has been proposed as a progenitor theory of FRBs (Pen & Connor 2015). Alternatively, the radio nebula could correspond to a supernova remnant, magnetar wind nebula, or HII region. Such local environments have been invoked as a way to provide local RM, DM, and scattering (Connor et al. 2016b; Piro 2016; Murase et al. 2016; Piro & Gaensler 2018; Margalit & Metzger 2018; Straal et al. 2020). In each of these cases, it is difficult to predict the distribution of observed RMs, but it is likely that the distribution would be broad. For example, in the circumnuclear magnetar model, the RM of the FRB is a strong function of its distance from the massive black hole. In young magnetar or supernova remnant models, the RM is expected to change with time, and the value depends on when in the progenitor life cycle the FRB was observed. Thus, moderately large RMs like those of FRB 191108, FRB 110523 (Masui et al. 2015), and FRB 160102 (Caleb et al. 2018) may come from a similar environment to FRB 121102.

### 6.8.6 Repetition constraints

Given the extreme local environment of FRB 121102 and its anomalously high repetition rate, it may be asked if frequent repeaters are more likely to live near dense magnetised plasma. CHIME recently discovered a repeating FRB whose RM is \(-499.8 \pm 0.7\) rad m\(^{-2}\), which is roughly two orders of magnitude larger than the expected Milky Way contribution in that direction (Fonseca et al. 2020). But Fonseca et al. (2020) also report a repeater with
RM$=\pm 20 \pm 1 \text{ rad m}^{-2}$, and most of the RM$=-114.6 \pm 0.6 \text{ rad m}^{-2}$ from another CHIME repeating source, FRB 180916.J0158+65, is thought to be from the Milky Way (CHIME/FRB Collaboration et al. 2019c).

We observed the field of FRB 191108 for 120 hrs between July 2019 and December 2019 with Apertif, but had no repeat detections. Apertif has detected and studied other repeating FRBs (Chapter 5). Assuming repetition statistics described by a homogeneous Poisson process, our non-detection provides a 3$\sigma$ upper-limit on the repeat rate of $3 \times 10^{-2} \text{ hr}^{-1}$. We caution, however, that the assumption of stationarity is known to not be valid for some FRBs, which show time-variability in their repetition rate (Spitler et al. 2016; Oppermann et al. 2018; Gourdji et al. 2019; Chapter 5), thereby increasing the probability of seeing zero repeat bursts during follow up (Connor et al. 2016a).

We plan to continue follow-up efforts on the same field, which we can do commensally with our full-FoV blind FRB search. The source is currently localised to an ellipse with semi-minor and semi-major axes of 2.5$''$ and 3.5$'$, respectively, as described in Sect. 6.8.2. If we detect FRB 191108 again at a different hour angle than the initial detection, we will have several arcsecond localisation in both directions, because the TABs rotate as a function of parallactic angle.

The source position is slightly outside the area around M33 that Mikhailov & van Leeuwen (2016) searched for FRBs and pulsars with the LOw Frequency ARray (LOFAR). Using the LOFAR Transient Buffer Boards (TBBs), the field of FRB 191108 will be observed simultaneously with Apertif and LOFAR. The TBBs allow LOFAR to save voltage data across multiple stations between 100–200 MHz and search for emission over a decade in frequency.