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USING 2D-FFT TO SEARCH FAST RADIO BURST*

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ABSTRACT

Fast Radio Burst have been found from pulsar data for many years. There are several FRB search algorithm like tree algorithm, FDMT et. Here we proposed a different FRB searching algorithm which basically trace a curve in frequency-time image. This algorithm is mainly realized by two dimensional Fast Fourier Transform. We take a 2D FFT on the $f^{-2}(t)$ data map, Then trace the signal along the angle of straight line. In this searching method, it's easier to remove RFI in large scale and will bring a speed up benefit in well-developed 2D FFT library both in CPU and GPU code.

Fast Radio Burst is a high energy radio signal found in the Universe. The first one is found by Lorimer Duncn in 2007, now people always call it as Lormeter burst. Like Pulsar, Its a wide band radio sginal, when it go through the inter stellar or inter galaxy medium, the higher frequency will go faster than lower frequency. When Signal go through dense of ISM The origin of FRB is still unclear, there are lots of theories trying to describe what FRB is.

Keywords: 2DFFT ,FAST radio burst

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1. INTRODUCTION

Fast radio bursts (FRBs) are bright (∼Jy) and short (∼ms) bursts of radio emission that have dispersion measures (DMs) in excess of the line of sight DM contribution expected from the electron distribution of our Galaxy. To date 18 FRBs have been reported — most of them detected at the Parkes telescope (**?????????**) and one each at the Arecibo (**?**) and Green Bank telescopes (**?**).

A plethora of source models have been proposed to explain the properties of FRBs (see e.g. **?**, for a brief review). According to the models, the excess DM for FRBs may be intrinsic to the source, placing it within the Galaxy; it may arise mostly from the intergalactic medium, placing a source of FRBs at cosmological distances ($z \sim 0.2-1$) or it may arise from the host galaxy, placing a source of FRBs at extragalactic, but not necessarily cosmological, distances ($\sim 100\,\mathrm{Mpc}$).

Since the only evidence to claim an extragalactic origin for FRBs has been the anomalously high DM, some models also attempted to explain the excess DM as a part of the model, thus allowing FRBs to be Galactic. All FRBs observed to date have been detected with single dish radio telescopes, for which the localization is of order arcminutes, insufficient to obtain an unambiguous association with any object. To date, no independent information about their redshift, environment, and source could be obtained due to the lack of an accurate localization of FRBs. **?** attempted to identify the host of FRB 150418 on the basis of a fading radio source in the field that was localized to a $z = 0.492$ galaxy. However, later work identified the radio source as a variable active galactic nucleus (AGN) that may not be related to the source (**????**).

Repeated radio bursts were observed from the location of the Arecibo-detected FRB Search Algorithm (**??**), with the same DM as the first detection, indicating a common source. As discussed by **?**, it is unclear whether the repetition makes FRB Search Algorithm unique among known FRBs, or whether radio telescopes other than Arecibo lack the sensitivity to readily detect repeat bursts from other known FRBs.

? used the Karl G. Jansky Very Large Array (VLA) to directly localize the repeated bursts from FRB Search Algorithm with 100-mas precision and reported an unresolved, persistent radio source and an extended optical counterpart at the location with a chance coincidence probability of $\approx 3 \times 10^{-4}$ — the first unambiguous identification of multi-wavelength counterparts to FRBs. Independently, **?** used the European VLBI Network (EVN) to localize the bursts and the persistent source and showed that both are co-located within ~ 12 milliarcseconds.

Here we report a new algorithm to search FRBs .

2. BASICS OF INCOHERENT DEDISPERSION

The dispersion of the electromagnaetic wave pulse cause a delay in arrival time at frequency ν compared with thre reference frequency ν_0, which is given by :

$$\Delta t(\nu) = -D(\nu^{-2} - \nu_0^{-2}) \tag{1}$$

where D is the dispersion measure. Thus , We may model a burst with a very short intrinsic width as :

$$I(t,\nu) = I_0(\nu)\delta_D(t - t_s - \frac{D}{\nu^2}) \tag{2}$$

Where δD is the Dirac delta function, t_s marks the signal starting time for infinitely high frequency. If the bandwidth is small, we can approximate

$$\frac{D}{\nu^2} \approx \frac{D}{\nu_0^2}(1 - 2\frac{\nu - \nu_0}{\nu_0})$$

denote $\Delta\nu \equiv \nu - \nu_0$, and assume that the spectrum is not too steep such that within the observing band the signal is constant, then

$$\begin{aligned} I(t,\nu) &\approx I_0\delta_D(t - t_s - \frac{D}{\nu_0^2}(1 - 2\frac{\Delta\nu}{\nu_0})) \\ &= I_0\delta_D(t - t_0 + \frac{2D}{\nu_0^3}\Delta\nu) \end{aligned} \tag{3}$$

where t_0 is the arrival time of the signal at thre reference frequency ν_0.
Now consider an integral of this signal between frequency ν_1 and ν_2 , the signal strength would be

$$s = \int d\nu \int dt I(t,\nu) = (\nu_2 - \nu_1)I_0 = I_0 B \tag{4}$$

Where $B = \nu_2 - \nu_1$ is the bandwidth. Now consider the noise. Suppose the data is digitized with time interval δt and frequency channel bandwidth $\delta\nu$. For the incoherent dedispersion, the signal within each time interval and frequency channel is

$$I_n = \frac{2kT_{sys}}{A_{\mathrm{eff}}\sqrt{\delta\nu\delta t}} \tag{5}$$

Suppose we are observing between ν_1,ν_2 with a total of N_ν channels, and processing a time interval $T = N_t\delta t$ where $T \geq \Delta t(\nu_1) - \Delta t(\nu_2)$, i.e. the whole of the dispersed signal is within the data frame.
For incoherent dedispersion , in the absence of the pulse signal, the whole read out of the data frame is given by

$$\begin{aligned} n &= \int d\nu \int dt I_n = \frac{2kT_{sys}}{A_{\mathrm{eff}}}\frac{(\nu_2 - \nu_1)T}{\sqrt{\delta\nu\delta t}} \\ &= \frac{2kT_{sys}}{A_{\mathrm{eff}}} B^{1/2}T^{1/2}N_\nu^{1/2}N_t^{1/2} \end{aligned} \tag{6}$$

So the raw signal to noise ratio is given

$$\mathrm{SNR}_{raw} = \frac{I_0 A_{\rm eff}}{2kT_{sys}} \left(\frac{B}{N_\nu N_t T}\right)^{1/2} \quad (7)$$

In a perfect incoherent dedispersion , we sum up all the signal, which is still given by s. However, we compare it with the noise in the same dedispersion $\nu - t$ track, not the whole data frame. The noise along the same track is given by

$$n = \int d\nu \int dt I_n \delta_D(t - t_0 + \frac{2D}{\nu_0^3}\Delta\nu) = BI_n \quad (8)$$

Then

$$\mathrm{SNR}_{opt} = \frac{I_0}{I_N} = \frac{I_0 A_{\rm eff}}{2kT_{sys}} \left(\frac{BT}{N_\nu N_t}\right)^{1/2} \quad (9)$$

Now consider a pulse of finite width. We replace the Dirac δ function by a Gaussian function with the same normalization

$$\delta_D(t-t') \to g(t-t') \equiv \frac{1}{(2\pi)^{1/2}\sigma} \exp[-\frac{(t-t')^2}{2\sigma_t^2}] \quad (10)$$

If the pulse intrinsic width $\sigma > \delta t$, then in a dedispersion along the track only the part of the signal within one time bin would be included, which gives

$$\int_{-\delta t}^{+\delta t} d\Delta t \frac{1}{\sqrt{2\pi}\sigma} e^{-\Delta t^2/2\sigma^2} = erf(\frac{\delta t}{\sqrt{2}\sigma}) \approx \sqrt{\frac{2}{\pi}}\frac{\delta t}{\sigma} \quad (11)$$

Where the last holds for the case $\delta t \ll \sigma$, so in this case

$$s = I_0 B \sqrt{\frac{2}{\pi}}\frac{\delta t}{\sigma} \quad (12)$$

While the noise is still given by Eq.(8), so in this case

$$\mathrm{SNR}_{fin} = \frac{I_0}{I_n} = \frac{I_0 A_{\rm eff}}{2kT_{sys}} \left(\frac{BT}{N_t N_\nu}\right)^{1/2} \sqrt{\frac{2}{\pi}}\frac{\delta t}{\sigma} \quad (13)$$

3. 2D FFT DEDISPERSION

The usual Fourier transform is :

$$\begin{aligned} \widetilde{f}(\omega) &= \frac{1}{2\pi}\int f(t) e^{-i\omega t} dt \\ f(t) &= \int \widetilde{f}(\omega) e^{i\omega t} d\omega \end{aligned} \quad (14)$$

For$f(t) = \delta_D(t-t_0), \widetilde{\omega} = \frac{1}{2\pi} e^{-i\omega t_0}$. Using the relation :

$$\int d\omega e^{i\omega t_0} = 2\pi \delta_D(t_0) \quad (15)$$

we find the above indeed form a Fourier pair. However , here we want to use ν instead of ω, then the Fourier transform pair are:

$$\begin{aligned} \widetilde{f}(\nu) &= \frac{1}{2\pi}\int f(t) e^{-i2\pi\nu t} dt \\ f(t) &= 2\pi \int \widetilde{f}(\nu) e^{i2\pi\nu t} d\nu \end{aligned} \quad (16)$$

The 2d transform of the signal $I(\nu, t)$ is

$$\widetilde{I}(f,\tau) = \int d\nu\ e^{2\pi i\nu\tau} \int dt\ e^{-2\pi i f t} I(t,\nu) \quad (17)$$

where we denote the Fourier conjugate variable of ν, t as τ, f to avoid confusion. For the pulse signal given by Eq.(2),

$$\begin{aligned} \widetilde{I}(f,\tau) &= \int d\nu e^{2\pi i\nu\tau} I_0 e^{-2\pi i f (t_0 - \frac{2D}{\nu_0^3}\Delta\nu)} \\ &= I_0 e^{-i2\pi f (t_0 + \frac{2D}{\nu_0^2})} \int d\nu\ e^{i2\pi\nu(\tau + \frac{2Df}{\nu_0^2})} \\ &= \frac{I_0}{2\pi} exp[-i2\pi f(t_0 + \frac{2D}{\nu_0^2})] \delta_D(\tau + \frac{2Df}{\nu_0^2}) \end{aligned} \quad (18)$$

Note $\widetilde{I}(\tau, f)$ is non-zero only on the staight line $\tau + \frac{2Df}{\nu_0^2} = 0$, and the value is a complex number whose phase angle gives the arrival time. For the pulse with finite width,

$$\widetilde{I}(f,\tau) = \int d\nu e^{2\pi i\nu\tau} \int dt\ e^{-2\pi i f t} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-t')^2}{2\sigma^2}} \quad (19)$$

where $t' = t_0 + \frac{2D}{\nu_0^3}\Delta\nu$. Complete the t integral , we get

$$\begin{aligned} \widetilde{I}(f,\tau) &= \int d\nu\ e^{2\pi i\nu\tau} I_0 e^{-i2\pi f t'} e^{-\frac{(2\pi f\sigma)^2}{2}} \\ &= I_0 e^{-i2\pi f(t_0 - \frac{2D}{\nu_0^2})} e^{-\frac{(2\pi f\sigma)^2}{2}} \int d\nu\ exp[i2\pi\nu(\tau + \frac{2Df}{\nu_0^2})] \\ &= \frac{I_0}{2\pi} e^{-i2\pi f(t_0 - \frac{2D}{\nu_0^2})} e^{-\frac{(2\pi f\sigma)^2}{2}} \delta_D(\tau + \frac{2Df}{\nu_0^2}) \end{aligned} \quad (20)$$

Note this is similar to Eq(18) except for the factor $e^{-\frac{(2\pi f\sigma)^2}{2}}$, this limits the usable range of f to $|f| < (2\pi\sigma)^{-1}$.

4. TRANSFORM TO POLAR COORDINATES

We can take $\frac{2f}{\nu_0^2}, \tau$ as the x, y in Cartesian coordinates, then the polar cpprdinates ρ, θ can be defined as

$$\begin{aligned} \rho^2 &= \left(\frac{2f}{\nu_0^2}\right)^2 + \tau^2 \\ \tan\theta &= \frac{\tau}{2f/\nu_0^2} \end{aligned} \quad (21)$$

with $\tan\theta = -D$ for the track satisfy Eq.(20). Conversely,

$$f = \frac{\nu_0^2}{2}\rho\cos\theta \qquad (22)$$
$$\tau = \rho\sin\theta$$

Then

$$\widetilde{I}(\rho,\theta) = \frac{I_0}{2\pi} e^{-i2\pi\left(\frac{\nu_0^2\cdot t}{2}-D\right)\rho\cos\theta} \cdot e^{-\frac{\pi^2\sigma^2\nu_0^4}{2}\rho^2\cos^2\theta}\rho^{-1}\delta_D(\theta+\arctan D) \qquad (23)$$

4.1. *Ionized Gas Properties in the Host*

The Balmer lines from the host also allow us to estimate the properties its ionized ISM and its contribution to the total DM of FRB Search Algorithm.

The Hα surface density for the galaxy with flux $F_{\mathrm{H}\alpha}$, semi-major axis a, and semi-minor axis b is

$$\begin{aligned} S(\mathrm{H}\alpha) &= \frac{F_{\mathrm{H}\alpha}}{\pi ab}, \\ &\approx 6.8\times10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,arcsecond^{-2}}, \\ &\approx 120\,\mathrm{Rayleigh}, \end{aligned} \qquad (24)$$

where we have used the extinction corrected flux $F_{\mathrm{H}\alpha} = 2.6\times10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ and the semi-major and minor axes ($a = 0\overset{''}{.}44$, $b/a = 0.68$) from the i' and r' images. In the source frame (denoted below by the subscript, 's'), the surface density is

$$S(\mathrm{H}\alpha)_\mathrm{s} = (1+z)^4 S(\mathrm{H}\alpha) = 243\,\mathrm{Rayleigh}. \qquad (25)$$

For a temperature $T = 10^4 T_4$ K, we express the emission measure (EM $= \int n_e^2 \mathrm{d}s$) given by **?** in the galaxy's frame

$$\begin{aligned} \mathrm{EM}(\mathrm{H}\alpha)_\mathrm{s} &= 2.75\mathrm{pc\,cm^{-6}}\,T_4^{0.9}\left[\frac{S(\mathrm{H}\alpha)_\mathrm{s}}{\mathrm{Rayleigh}}\right], \\ &\approx 670\,\mathrm{pc\,cm^{-6}}\,T_4^{0.9}. \end{aligned} \qquad (26)$$

We get a smaller value from the extinction-corrected Hβ flux, $\mathrm{EM(H\beta)_s} \approx 530\,\mathrm{pc\,cm^{-6}}$. For the calculations below, we proceed with a combined estimate, $\mathrm{EM_s} \approx 600\,\mathrm{pc\,cm^{-6}}$.

This value is fairly large compared to measurements of the local Galactic disk. The WHAM Hα survey, for example, gives values of tens of pc cm^{-6} in the Galactic plane and about 1 pc cm^{-6} looking out of the plane (**?**). However, lines of sight to distant pulsars and studies of other galaxies give EM values in the hundreds (**??**).

The estimate for EM$_\mathrm{s}$ is sensitive to the inferred solid angle of the galaxy and emitting regions. Ongoing observations with the *Hubble Space Telescope* will better resolve the Hα emitting structures and improve our constraint on the EM with respect to the location of the burst.

The implied optical depth for free-free absorption at an observation frequency ν (in GHz) is

$$\begin{aligned} \tau_\mathrm{ff} &\approx 3.3\times10^{-6}[(1+z)\nu_\mathrm{GHz}]^{-2.1}T_4^{-1.35}\mathrm{EM_s} \\ &\approx 1.4\times10^{-3}\nu_\mathrm{GHz}^{-2.1}T_4^{-0.45}. \end{aligned} \qquad (27)$$

Free-free absorption for FRB Search Algorithm is therefore negligible even at 100 MHz. This suggests that the radio spectra of the bursts and possibly the persistent source are unaffected by absorption and are inherent to the emission process or to propagation effects near the sources, confirming the inference made by (**?**) based on the widely varying spectral shapes of the bursts alone.

4.1.1. *Implied DM from* Hα*-emitting Gas*

The EM implies a DM value sometimes given by DM $= (\mathrm{EM} f_\mathrm{f} L)^{1/2}$, where f_f is the volume filling factor of ionized clouds in a region of total size L (**?**). As summarized in Appendix B of **?**, additional fluctuations decrease the DM derived from EM, giving a source-frame value,

$$\widehat{\mathrm{DM}}_\mathrm{s} \approx 387\ \mathrm{pc\ cm^{-3}}\,L_\mathrm{kpc}^{1/2}\left[\frac{f_\mathrm{f}}{\zeta(1+\epsilon^2)/4}\right]^{1/2} \times\left(\frac{\mathrm{EM}}{600\ \mathrm{pc\ cm^{-6}}}\right)^{1/2}, \qquad (28)$$

where $\epsilon \le 1$ is the fractional variation inside discrete clouds due to turbulent-like density variations and $\zeta \ge 1$ defines cloud-to-cloud density variations in the ionized region of depth L_kpc in kpc. Here we have used $\mathrm{EM_s} = 600$ pc cm^{-6} and assumed 100% cloud-to-cloud variations ($\zeta = 2$) and fully modulated electron densities inside clouds ($\epsilon = 1$).

The host contribution to the *measured* DM is a factor $(1+z)^{-1}$ smaller than the source frame DM[1]. Also, the line of sight to the FRB source may sample only a fraction of $\widehat{\mathrm{DM}}_\mathrm{s}$ depending on if it is embedded in or offset from the Hα-emitting gas. For an effective path length through the ionized gas $L_\mathrm{FRB} \le L$, we then have

$$\begin{aligned} \widehat{\mathrm{DM}}(\mathrm{FRB}) &= \frac{\widehat{\mathrm{DM}}_\mathrm{s}}{1+z}\left(\frac{L_\mathrm{FRB}}{L}\right) \\ &\approx 324\ \mathrm{pc\ cm^{-3}}\left(\frac{L_\mathrm{FRB}}{L}\right)\left[\frac{4L_\mathrm{kpc}f_\mathrm{f}}{\zeta(1+\epsilon^2)}\right]^{1/2}. \end{aligned} \qquad (29)$$

[1] The factor of $(1+z)^{-1}$ is a combination of the photon redshift, time dilation and the frequency^{-2} dependence of cold plasma dispersion.

This estimate can be compared with empirical constraints discussed in **?** on contributions from the host and the intergalactic medium (IGM) to the total DM made by subtracting the NE2001 model's DM contribution from the Milky Way (**?**) ($\mathrm{DM_{MW}} = 188$ pc cm^{-3}) and the Milky Way halo ($\mathrm{DM_{MW_{halo}}} = 30$ pc cm^{-3}) from the total DM $= 558\,\mathrm{pc\,cm^{-3}}$. This gives $\mathrm{DM_{IGM}} + \mathrm{DM_{host}} = 340\,\mathrm{pc\,cm^{-3}}$. The Milky Way contributions have uncertain errors but are likely of order 20%. The measured redshift implies a mean IGM contribution $\mathrm{DM_{IGM}} \approx 200$ pc cm^{-3} (**??**) but can vary by about ± 85 pc cm^{-3} (**?**). This yields a range of possible values for $\mathrm{DM_{host}}$: $55 \lesssim \mathrm{DM_{host}} \lesssim 225\,\mathrm{pc\,cm^{-3}}$ that further implies $0.09 \lesssim (L_{\mathrm{FRB}}/L)\left[L_{\mathrm{kpc}} f_{\mathrm{f}}/\zeta(1+\epsilon^2)\right]^{1/2} \lesssim 0.35$. The ionized region therefore must have some degree of clumpiness or the effective path length is significantly smaller than the size of the ionized region.

Radio pulsars in the Large and Small Magellanic Clouds have DMs spanning the range 45–273 pc cm^{-3} and 70–200 pc cm^{-3}, respectively (**?**). This empirically demonstrates that the free electron content of star-forming dwarf galaxies is of the order we estimate. The relatively large DM contribution from the host galaxy (as inferred from the Hα emission) implies that any contributions from the vicinity of the FRB source itself are probably quite small. This may rule out a very young ($< 100\,\mathrm{yr}$) supernova remnant (e.g. **?**).

4.2. *Implications for Source Models*

? reported the locations of the radio bursts, the optical and variable radio counterparts and the absence of millimeter-wave and X-ray emission. **?** have shown that the bursts and the persistent radio source are colocated to within a linear projected separation of 40 pc, suggesting that the two emission sources should be physically related, though not necessarily the same source. The radio source properties are consistent with a low luminosity AGN or a young (<1000 yr) supernova remnant (SNR) powered by an energetic neutron star (e.g. **?**).

The optical properties of the galaxies reported here do not add support to the AGN interpretation although it cannot be conclusively ruled out. The BPT diagnostics for the host (Figure **??**) show no indication of AGN activity. However, this may not be conclusive as the majority of radio-loud AGN show no optical signatures of activity (**?**). This is further supported by five low luminosity AGN with no optical signatures have also recently been discovered (**?**). However, these objects are almost exclusively hosted in galaxies with much larger stellar masses ($\sim 10^{10}\,M_\odot$). We also note that the radio source is offset from the optical center of the galaxy by 170–300 mas, corresponding to a transverse linear distance of 0.5–1 kpc, nearly a quarter to half of the radial extent, which is not consistent with a central AGN, but such offsets have been seen before in dwarf galaxies, e.g. Henize 2-10 (**?**).

The association of an optical/X-ray AGN with a dwarf galaxy is also extremely rare. A search of emission-line dwarf galaxies ($10^{8.5} \lesssim M_* \lesssim 10^{9.5}\,M_\odot$) using BPT line diagnostics identified an AGN rate of ~ 0.5 % (**?**), with an additional 0.05 % of dwarf galaxies searched exhibiting narrow emission lines consistent with star formation band broad Hα consistent with an AGN. Similarly, an X-ray survey of $z < 1$ dwarf galaxies reported an AGN rate of 0.6–3% (**?**). Of the dwarf galaxies known to host AGN, only two exhibit nuclear radio emission that appears to originate from a black-hole jet, Henize 2-10 and Mrk 709 (**??**). Both have strong nuclear X-ray emission that originates from the AGN but optical emission lines that are dominated by star-formation processes. The combination of a compact radio source, absent nuclear X-ray emission, strong star-formation optical emission lines, and weak or non-existent broad optical emission lines that we observe in the host of FRB Search Algorithm has no analogue in any known galaxy to the best of our knowledge.

The high star formation rate is consistent with the presence of a young SNR or a cluster of young massive stars (i.e. an OB association), which would naturally link FRBs to neutron stars which are the favored progenitor models.

4.2.1. *Relation to Dwarf Galaxies*

It is interesting to note that the only FRB host directly identified so far is a low metallicity dwarf galaxy rather than, say, an extremely high-star-formation-rate galaxy such as Arp 220 or a galaxy with a very powerful AGN or some other extreme characteristics. Dwarf galaxies are also a small fraction of the stellar mass in the Universe (**?**). **?** also suggested that the extremely low scattering of FRB 150807 compared to its DM may be linked to its origin from a low-mass ($< 10^9\,M_\odot$) galaxy. However, the strong polarization and scattering properties of FRB 110523 do suggest the presence of turbulent magnetized plasma around the source (**?**), suggesting that individual FRB environments may be quite diverse.

If FRBs are indeed more commonly hosted by dwarf galaxies in the low redshift Universe, they would share this preference with two other classes of high-energy transients — long duration gamma-ray bursts and superluminous supernovae, both of which prefer low-mass, low-metallicity, and high star formation rate hosts (e.g., **????**, and other works). Indeed, superluminous supernovae are prefentially hosted by EELGs (**?**). If this relation is true, it may point to a link between FRBs and extremely massive progenitor stars, possibly extending to magnetars that have been associated with massive progenitor stars (e.g. **?**).

4.3. *Future Optical Follow-Up of FRBs*

A link between FRBs and dwarf galaxies will impact future multi-wavelength follow-up plans. Without the precise localization for FRB Search Algorithm (**?**), the host galaxy is scarcely distinguishable from other objects in the deep Gemini images.

Due to the trade-off between field of view and localization precision, FRB search projects that have a large FRB detection rate such as CHIME (Kaspi V. M. et al,. 2017, in preparation), UTMOST (**?**), and HIRAX (**?**) will localize high signal to noise detections to only subarcmin precision. If FRB hosts are star-forming galaxies with strong emission lines, slitless objective prism spectroscopy could efficiently distinguish these objects from a field of stars and elliptical galaxies, leading to putative host identifications without very precise localization. However, this strongly depends on the link between FRBs and their host properties and the homogeneity of FRBs — which will first have to be confirmed with more interferometric localizations.

We note, of course, that our above discussion regarding the possible relationship between FRBs and dwarf galaxies in general is based on a single data point of a repeating FRB, which may not be representative of the broader FRB population (see **??**, for more details).

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Facility: Gemini:Gillett (GMOS)

Software: ESO-MIDAS, astro-py, galfit, SExtractor

REFERENCES

Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Atek, H., Siana, B., Scarlata, C., et al. 2011, ApJ, 743, 121
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Barentsen, G., Farnhill, H. J., Drew, J. E., et al. 2014, MNRAS, 444, 3230
Bassa, C. G., Beswick, R., Tingay, S. J., et al. 2016, MNRAS, 463, L36
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Burke-Spolaor, S., & Bannister, K. W. 2014, ApJ, 792, 19
Caleb, M., Flynn, C., Bailes, M., et al. 2016, MNRAS, 458, 718
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Champion, D. J., Petroff, E., Kramer, M., et al. 2016, MNRAS, 460, L30
Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Nature, 000, 000
Cordes, J. M., & Lazio, T. J. W. 2002, ArXiv Astrophysics e-prints, astro-ph/0207156
Cordes, J. M., Wharton, R. S., Spitler, L. G., Chatterjee, S., & Wasserman, I. 2016, ArXiv e-prints, arXiv:1605.05890
Côté, S., Carignan, C., & Freeman, K. C. 2000, AJ, 120, 3027
Dopita, M. A., Kewley, L. J., Sutherland, R. S., & Nicholls, D. C. 2016, Ap&SS, 361, 61
Fruchter, A. S., Levan, A. J., Strolger, L., et al. 2006, Nature, 441, 463
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, ArXiv e-prints
Giroletti, M., Marcote, B., Garrett, M. A., et al. 2016, A&A, 593, L16
Graham, J. F., & Fruchter, A. S. 2015, ArXiv e-prints, arXiv:1511.01079
Haffner, L. M., Dettmar, R.-J., Beckman, J. E., et al. 2009, Reviews of Modern Physics, 81, 969
Hamuy, M., Suntzeff, N. B., Heathcote, S. R., et al. 1994, PASP, 106, 566
Hamuy, M., Walker, A. R., Suntzeff, N. B., et al. 1992, PASP, 104, 533
Hill, A. S., Benjamin, R. A., Kowal, G., et al. 2008, ApJ, 686, 363
Horne, K. 1986, PASP, 98, 609
Hynes, R. I. 2002, A&A, 382, 752
Inoue, S. 2004, MNRAS, 348, 999
Ioka, K. 2003, ApJL, 598, L79
Johnston, S., Keane, E. F., Bhandari, S., et al. 2017, MNRAS, 465, 2143
Katz, J. I. 2016, Modern Physics Letters A, 31, 1630013
Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055
Keane, E. F., Stappers, B. W., Kramer, M., & Lyne, A. G. 2012, MNRAS, 425, L71
Keane, E. F., Johnston, S., Bhandari, S., et al. 2016, Nature, 530, 453
Kennicutt, Jr., R. C., Tamblyn, P., & Congdon, C. E. 1994, ApJ, 435, 22
Kewley, L. J., & Dopita, M. A. 2002, ApJS, 142, 35
Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, ApJ, 556, 121
Kewley, L. J., & Ellison, S. L. 2008, ApJ, 681, 1183
Kewley, L. J., Geller, M. J., Jansen, R. A., & Dopita, M. A. 2002, AJ, 124, 3135
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Kobulnicky, H. A., & Kewley, L. J. 2004, ApJ, 617, 240
Lelli, F., Verheijen, M., & Fraternali, F. 2014, A&A, 566, A71
Leloudas, G., Schulze, S., Krühler, T., et al. 2015, MNRAS, 449, 917
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Marcote, B., Paragi, Z., Hessels, J. W. T., Keimpema, A., & van Langevelde, H. J. e. a. 2017, ApJ, 000, 000
Masui, K., Lin, H.-H., Sievers, J., et al. 2015, Nature, 528, 523
Mauch, T., & Sadler, E. M. 2007, MNRAS, 375, 931
McQuinn, M. 2014, ApJL, 780, L33
Mignard, F., Klioner, S., Lindegren, L., et al. 2016, ArXiv e-prints, arXiv:1609.07255
Moffat, A. F. J. 1969, A&A, 3, 455
Murase, K., Kashiyama, K., & Mészáros, P. 2016, MNRAS, 461, 1498
Newburgh, L. B., Bandura, K., Bucher, M. A., et al. 2016, in Proc. SPIE, Vol. 9906, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 99065X
Olausen, S. A., & Kaspi, V. M. 2014, ApJS, 212, 6
Papastergis, E., Cattaneo, A., Huang, S., Giovanelli, R., & Haynes, M. P. 2012, ApJ, 759, 138
Pardo, K., Goulding, A. D., Greene, J. E., et al. 2016, ApJ, 831, 203
Park, S., Yang, J., Oonk, J. B. R., & Paragi, Z. 2016, ArXiv e-prints, arXiv:1611.05986

Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266

—. 2010, AJ, 139, 2097

Perley, D. A., Levan, A. J., Tanvir, N. R., et al. 2013, ApJ, 778, 128

Perley, D. A., Quimby, R. M., Yan, L., et al. 2016, ApJ, 830, 13

Petroff, E., Bailes, M., Barr, E. D., et al. 2015, MNRAS, 447, 246

Pettini, M., & Pagel, B. E. J. 2004, MNRAS, 348, L59

Piro, A. L. 2016, ApJL, 824, L32

Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13

Ravi, V., Shannon, R. M., & Jameson, A. 2015, ApJL, 799, L5

Ravi, V., Shannon, R. M., Bailes, M., et al. 2016, ArXiv e-prints, arXiv:1611.05758

Reines, A. E., Greene, J. E., & Geha, M. 2013, ApJ, 775, 116

Reines, A. E., Plotkin, R. M., Russell, T. D., et al. 2014, ApJL, 787, L30

Reines, A. E., Sivakoff, G. R., Johnson, K. E., & Brogan, C. L. 2011, Nature, 470, 66

Reynolds, R. J. 1977, ApJ, 216, 433

Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103

Schlafly, E. F., Finkbeiner, D. P., Schlegel, D. J., et al. 2010, ApJ, 725, 1175

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Scholz, P., Spitler, L. G., Hessels, J. W. T., et al. 2016, ApJ, 883, 177

Spitler, L. G., Cordes, J. M., Hessels, J. W. T., et al. 2014, ApJ, 790, 101

Spitler, L. G., Scholz, P., Hessels, J. W. T., et al. 2016, Nature, 531, 202

Thornton, D., Stappers, B., Bailes, M., et al. 2013, Science, 341, 53

Vergani, S. D., Salvaterra, R., Japelj, J., et al. 2015, A&A, 581, A102

Williams, P. K. G., & Berger, E. 2016, ApJL, 821, L22