Future Cosmological Constraints From Fast Radio Bursts

Anthony Walters1,2, Amanda Weltman1, B. M. Gaensler3, Yin-Zhe Ma2,4, and Amadeus Witzemann1,5
1 Department of Mathematics and Applied Mathematics, University of Cape Town, Cape Town, South Africa; tony.walters@uct.ac.za
2 School of Chemistry and Physics, University of KwaZulu-Natal, Durban, 4000, South Africa
3 Dunlap Institute for Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada
4 NAOC–UKZN Computational Astrophysics Centre (NUCAC), University of KwaZulu-Natal, Durban, 4000, South Africa
5 Department of Physics and Astronomy, University of the Western Cape, Cape Town, South Africa

Received 2017 November 30; revised 2018 February 6; accepted 2018 February 12; published 2018 March 26

Abstract

We consider the possible observation of fast radio bursts (FRBs) with planned future radio telescopes, and investigate how well the dispersions and redshifts of these signals might constrain cosmological parameters. We construct mock catalogs of FRB dispersion measure (DM) data and employ Markov Chain Monte Carlo analysis, with which we forecast and compare with existing constraints in the flat $\Lambda$CDM model, as well as some popular extensions that include dark energy equation of state and curvature parameters. We find that the scatter in DM observations caused by inhomogeneities in the intergalactic medium (IGM) poses a big challenge to the utility of FRBs as a cosmic probe. Only in the most optimistic case, with a high number of events and low IGM variance, do FRBs aid in improving current constraints. In particular, when FRBs are combined with CMB+BAO+SNe+$H_0$ data, we find the biggest improvement comes in the $\Omega_b h^2$ constraint. Also, we find that the dark energy equation of state is poorly constrained, while the constraint on the curvature parameter, $\Omega_k$, shows some improvement when combined with current constraints. When FRBs are combined with future baryon acoustic oscillation (BAO) data from 21 cm Intensity Mapping, we find little improvement over the constraints from BAOs alone. However, the inclusion of FRBs introduces an additional parameter constraint, $\Omega_b h^2$, which turns out to be comparable to existing constraints. This suggests that FRBs provide valuable information about the cosmological baryon density in the intermediate redshift universe, independent of high-redshift CMB data.

Key words: cosmological parameters – cosmology: theory – dark energy – radio continuum: general

1. Introduction

Improvements in cosmological measurement in recent years have been said to hail an era of “precision cosmology,” with observations of the cosmic microwave background (CMB) temperature anisotropies (Hinshaw et al. 2013; Planck Collaboration et al. 2016a, 2016b), baryon acoustic oscillation (BAO) wigles in the galaxy power spectrum (Beutler et al. 2011; Anderson et al. 2014; Ross et al. 2015), luminosity distance–redshift relation of Type Ia supernovae (SNeIa; Riess et al. 2004, 2007; Kowalski et al. 2008; Betoule et al. 2014), local distance ladder (Riess et al. 2016), galaxy clustering and weak lensing (DES Collaboration et al. 2017), and direct detection of gravitational waves (Abbott et al. 2017), providing constraints on cosmological model parameters at percent, or subpercent, level precision. Since the discovery of the accelerated expansion of the universe, these observations have cemented the emergence of the flat $\Lambda$CDM model as the standard model of cosmology, in which global spatial curvature is zero, and the energy budget of the universe is dominated by “dark energy” in the form of a cosmological constant, $\Lambda$. However, beyond the $\Lambda$CDM paradigm, there is a large number of dark energy models aimed at explaining the accelerated expansion of the universe (see reviews by Li et al. 2011 and Joyce et al. 2015, and references therein), and so understanding the nature of dark energy remains one of the central pursuits in modern cosmology. To this end, it has become common observational practice to constrain the dark energy equation of state, $w(z)$, and check for deviations from the $\Lambda$CDM value of $w = \text{const.} = -1$. While observational probes do not indicate any significant departure from $\Lambda$CDM (Huterer & Shafer 2017), there is still room to tighten constraints and thereby rule out competing alternatives for dark energy. In particular, by tuning the parameters of alternative theories of dark energy, one can recover the behavior of the $\Lambda$CDM model at both the background expansion and perturbation levels (Li et al. 2011; Joyce et al. 2015).

Observations of the CMB together with SNeIa and BAO constrain the spatial curvature parameter to be very small, $|\Omega_k| < 0.005$ (Planck Collaboration et al. 2016a), which is consistent with the flat $\Lambda$CDM model, and the inflationary picture of the early universe. However, model independent constraints from low redshift probes are not nearly as strong, with SNeIa alone preferring an open universe with $\Omega_k \sim 0.2$ (Rässinen et al. 2015). Similarly, constraints on the baryon fraction, $\Omega_b$, derived from observations of the CMB, and the abundance of light elements together with the theory of Big Bang Nucleosynthesis (BBN; Cooke et al. 2016), are both rooted in high-redshift physics. And, while these constraints are somewhat consistent, the BBN results strongly depend on nuclear cross-section data (Cooke et al. 2016; Dvorkin et al. 2016). Thus, independent and precise low redshift probes of spatial curvature and the baryon density parameter, which confirm the constraints from high-redshift data, are of observational and theoretical interest.

Recently, a promising new astrophysical phenomenon, so-called fast radio bursts (FRBs); Lorimer et al. 2007; Keane et al. 2011; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014; Masui et al. 2015; Petroff et al. 2015, 2017; Ravi et al. 2015, 2016; Champion et al. 2016; Keane et al. 2016; Caleb et al. 2017), has emerged. An FRB is characterized by a brief pulse in the radio spectrum with a large dispersion in the arrival time of its frequency components, consistent with
the propagation of an electromagnetic wave through a cold plasma. To date, a total of 25 such FRBs\(^6\) have been detected, primarily by the the Parkes Telescope in Australia, but more recently interferometric detections have also been reported. Considering the greatly improved sensitivity of upcoming radio telescopes, expectations are high that many more FRB events will be observed in the near future (Fialkov & Loeb 2017; Rajwade & Lorimer 2017). While their exact location and formation mechanism is still a subject of ongoing research (Kashiyama et al. 2013; Totani 2013; Lyubarsky 2014; Zhang 2014; Fuller & Ott 2015; Cordes & Wasserman 2016; Gu et al. 2016; Wang et al. 2016; Beloborodov 2017; Ghisellini & Locatelli 2017; Ghisellini 2017; Katz 2017; Kumar et al. 2017; Locatelli & Ghisellini 2017; Thompson 2017), their excessively large dispersion measures (DMs) argue that they have an extragalactic origin (Xu & Han 2015). Indeed, one FRB event has been sufficiently localized to be associated with a host galaxy at \(z = 0.19\) (Tendulkar et al. 2017). Should one be able to associate a redshift with enough FRBs, it would give access to the DM(z) relation, which may provide a new probe of the cosmos (Deng & Zhang 2014; Zhou et al. 2014; Gao et al. 2014; Yang & Zhang 2016; Yu & Wang 2017), possibly complementary to existing techniques. In addition, the observation of strongly lensed FRBs may help us to constrain the Hubble parameter (Li et al. 2017) and the nature of dark matter (Muñoz et al. 2016) and dispersion space distortions may provide information on matter clustering (Masui & Sigurdson 2015), all without redshift information.

In this paper, we assess the potential for using FRB DM(z) measurements, to constrain the parameter space of various cosmological models, and whether this may improve the existing constraints coming from other observations. The outline is as follows: The details of modeling an extragalactic population of FRBs, constructing a mock catalog of DM observations, and extracting and combining cosmological parameter constraints is given in Section 2. Parameter constraint forecasts from the mock FRB data, and its combination with CMB + BAO + SNIa + \(H_0\) (hereafter, referred to as CBSh), is given in Section 3.1 for the flat \(\Lambda\)CDM model, and in Section 3.2 for one- and two-parameter extensions to the flat \(\Lambda\)CDM model. Possible synergies with other experiments are discussed in Section 4.

## 2. Cosmology with FRBs

### 2.1. Dispersion of the Intergalactic Medium (IGM)

The DM of an FRB is associated with the propagation of a radio wave through a cold plasma, and is related to the path length from the emission event to observation, and the distribution of free electrons along that path, \(DM = \int n_{\text{e}} dl\). If FRBs are of extragalactic origin, their observed DM, \(DM_{\text{obs}}\), should be the sum of a number of different contributions, namely, from propagating through its host galaxy, \(DM_{\text{bg}}\), the IGM, \(DM_{\text{IGM}}\), and the Milky Way, \(DM_{\text{MW}}\) (Deng & Zhang 2014). Since \(DM_{\text{MW}}\) as a function of Galactic latitude is well known from pulsar observations (Yao et al. 2017), and its contribution to \(DM_{\text{obs}}\) is relatively small in most cases, we assume it can be reliably subtracted. We choose to work with the extragalactic DM, given by (Yang & Zhang 2016)

\[
DM_{\text{E}} \equiv DM_{\text{obs}} - DM_{\text{MW}} = DM_{\text{IGM}} + DM_{\text{HG}},
\]

where \(DM_{\text{HG}}\) is defined in the observers frame, and related to that at the emission event by

\[
DM_{\text{HG}} = \frac{DM_{\text{HG,loc}}}{1 + z}.
\]

This contribution is not well known and is expected to depend on the type of host galaxy, its inclination relative to the observer, and the location of the FRB inside the host galaxy (Xu & Han 2015; Yang & Zhang 2016), and so we include this as a source of uncertainty in our analysis.

The IGM is inhomogeneous and so \(DM_{\text{IGM}}(z)\) will have a large sightline-to-sightline variance, with estimates ranging between \(\sim 200\) and \(400\) pc \(\text{cm}^{-3}\) by \(z \sim 1.5\) (McQuinn 2014). It has, however, been shown that with enough FRB events in small enough redshift bins, the mean DM in each bin will approach the Friedmann–Lemaître–Robertson–Walker (FLRW) background value to good approximation. Specifically, with \(N \sim 80\) events in the redshift bin \(1 \leq z \leq 1.05\), the mean DM will be with 5% of the FLRW background value, at 95.4% confidence (Zhou et al. 2014). This is essential if one wishes to measure the cosmological parameters with any precision.

Assuming a non-flat FLRW universe that is dominated by matter and dark energy, one finds that the average (background) DM of the IGM is (Deng & Zhang 2014; Gao et al. 2014; Zhou et al. 2014)

\[
\langle DM_{\text{IGM}}(z) \rangle = \frac{3cH_0\Omega_{\text{bf}} f_{\text{b}}}{8\pi G m_p} \int_0^z \frac{\chi(z')(1 + z')}{E(z')} \, dz',
\]

where

\[
E(z) = [(1 + z)^3\Omega_m + f(z)\Omega_{\text{DE}} + (1 + z)^3\Omega_k]^{1/2},
\]

\[
\chi(z) = \chi_{\text{H}} \chi_{e,H}(z) + \frac{1}{2} \chi_p \chi_{e,H}(z),
\]

\[
f(z) = \exp \left[ 3 \int_0^z \frac{(1 + w(z'))dz'}{(1 + z')^3} \right],
\]

and \(H_0\) is the value of the Hubble parameter today, \(\Omega_{\text{b}}\) is the baryon mass fraction of the universe, \(f_{\text{b}}\) is the fraction of baryon mass in the IGM, \(Y_{\text{H}} = 3/4\) (\(Y_p = 1/4\)) is the hydrogen (helium) mass fraction in the IGM, and \(\chi_{e,H}(\chi_{e,H})\) is the ionization fraction of hydrogen (helium). The cosmological density parameters for matter and curvature are \(\Omega_m\) and \(\Omega_k\), respectively, and the dark energy density parameter is given by the constraint \(\Omega_{\text{DE}} \equiv 1 - \Omega_m - \Omega_k\).

We allow for the equation of state of dark energy, \(w\), to vary with time, and parameterize it by (Chevallier & Polarski 2001; Linder 2003)

\[
w(z) = w_0 + w_a \frac{z}{1 + z},
\]

where \(w_0\) and \(w_a\) are the CPL parameters. Substituting (7) into (6), and integrating, gives an exact analytic expression for the growth of dark energy density as a function of redshift

\[
f(z) = (1 + z)^3(1 + w_0 + w_a) \exp \left[ -3w_a \frac{z}{1 + z} \right].
\]

\(^6\) From version 2.0 of the FRB catalog (Petroff et al. 2016) found at http://www.frbcat.org/, accessed on 2017 November 17.
Choosing $\langle w_0, w_\tau \rangle = (-1, 0)$ in (6) gives $f(z) = \text{const.}$, corresponding to the $\Lambda$CDM model, in which dark energy is a cosmological constant.

For simplicity (to avoid modeling any astrophysics), we restrict our analysis to the region $z \leq 3$, since current observations suggest that both hydrogen and helium are fully ionized there (Meiksin 2009; Becker et al. 2011), and thus we can safely take $X_{c, H} = X_{c, He} = 1$ in (5). This gives a constant $\chi(z) = 7/8$ in the region of interest. The $f_{\text{IGM}}$ term presents some complications. Strictly speaking, $f_{\text{IGM}}$ is a function of redshift ($f_{\text{IGM}} = f_{\text{IGM}}(z)$) ranging from about 0.9 at $z \gtrsim 1.5$ to 0.82 at $z \lesssim 0.4$ (Meiksin 2009; Shull et al. 2012), and should be included inside the integral in (3). As a first approximation, we neglect the effect of evolving $f_{\text{IGM}}$, and set it to a constant.

### 2.2. Telescope Time and the Mock Catalog

Based on current detections, the FRB event rate in the universe is expected to be high, and given the improved design sensitivity of future radio telescopes, their detection rate is expected to increase significantly. This value, of course, will depend on the exact specifications of the telescope, and the true distribution and spectral profile of FRBs. For example, assuming they live only in low mass host galaxies, and have a Gaussian-like spectral profile, the mid-frequency component of the Square Kilometre Array (SKA) is expected to detect FRBs out to $z \sim 3.2$ at a rate of $\sim 10^3$ sky$^{-1}$ day$^{-1}$ (Fialkov & Loeb 2017). In the more immediate future, the Hydrogen Intensity Real-time Analysis eXperiment (HIRAX; Newburgh et al. 2016) and the Canadian Hydrogen Intensity Mapping Experiment (CHIME; Bandura et al. 2014), are expected to detect $\sim 50–100$ day$^{-1}$ and $\sim 30–100$ day$^{-1}$, respectively (Rajwade & Lorimer 2017). Assuming that 5% of the detected FRBs can be sufficiently localized to be associated with a host galaxy, the rate of detection and localization would be roughly $\sim 2–5$ day$^{-1}$ for HIRAX and CHIME, and far higher for the SKA. This suggests that a large catalog of localized FRBs could be built up relatively quickly, and the main bottleneck in obtaining a catalog of DM(z) data will be acquiring the redshifts. Given the bright emission lines in the spectrum of the host galaxy for the repeating FRB 121102 (Tendulkar et al. 2017), a mid-to-large-sized optical telescope should be able to obtain $\sim 10$ redshifts for FRB host galaxies per night; we thus estimate that a redshift catalog with $N_{\text{FRB}} = 1000$ will take approximately 100 nights of observing to construct, which would be feasible with a dedicated observing program spread over a few years.

Motivated by a phenomenological model for the distribution of gamma-ray bursts, we assume the redshift distribution of FRBs is given by $P(z) = z e^{-z}$ (Zhou et al. 2014; Yang & Zhang 2016), and simulate $\Delta M_E(z)$ measurements, given by the far right side of (1). Due to matter inhomogeneities in the IGM, and variations in the properties of the host galaxy, we promote $\Delta M_{\text{IGM}}$ and $\Delta M_{\text{HIG,loc}}$ to random variables, and sample them from a normal distribution. That is $\Delta M_{\text{IGM}} \sim \mathcal{N}(\langle \Delta M_{\text{IGM}} \rangle, \sigma_{\text{IGM}})$ and $\Delta M_{\text{HIG,loc}} \sim \mathcal{N}(\langle \Delta M_{\text{HIG,loc}} \rangle, \sigma_{\text{HIG,loc}})$. We assume $\langle \Delta M_{\text{IGM}} \rangle$ is given by (3) and a flat $\Lambda$CDM background as the fiducial cosmology, using the best-fit CBBS parameter values provided by the Planck 2015 data release,7 listed in the second column of Table 2. We also take $f_{\text{IGM}} = 0.83$ (Shull et al. 2012).

### Table 1

| FRB | $N_{\text{FRB}}$ | $\sigma_{\text{IGM}}$ (pc cm$^{-3}$) | $z_{\text{lim}}$ |
|-----|------------------|--------------------------------------|---------------|
| FRB1 | 1000             | 200                                  | 3             |
| FRB2 | 1000             | 400                                  | 3             |
| FRB3 | 100              | 200                                  | 3             |

Note. The number of FRB events is shown in the first column, the sightline-to-sightline variance in the second column, and the limiting redshift in the third column.

The value of $\Delta M_{\text{HIG,loc}}$ is expected to contain contributions from the Interstellar Medium (ISM) of the FRB host galaxy and near-source plasma. Since FRB progenitors and their emission mechanisms are as yet unknown, reasonable values of $\langle \Delta M_{\text{HIG,loc}} \rangle$ and $\sigma_{\text{HIG,loc}}$ are still debatable. Here we assume nothing about the host galaxy type or location of the FRB therein, just that there is a significant contribution to $\Delta M_{\text{HIG,loc}}$ due to near-source plasma, and thus take $\langle \Delta M_{\text{HIG,loc}} \rangle = 200$ pc cm$^{-3}$ and $\sigma_{\text{HIG,loc}} = 50$ pc cm$^{-3}$ (Yang & Zhang 2016). To investigate the effect of sample size and IGM inhomogeneities on resulting constraints, we construct a number of mock catalogs with various values for $\sigma_{\text{IGM}}$ and $N_{\text{FRB}}$. For the most optimistic sample, we choose $(N_{\text{FRB}}, \sigma_{\text{IGM}}) = (1000, 200)$. See Table 1 for a summary of the various catalogs.

### 2.3. Parameter Estimation and Priors

For the MCMC analysis, we use the $\chi^2$ statistic as a measure of likelihood for the parameter values. The log-likelihood function is given by

$$\ln L_{\text{FRB}}(\theta | d) = -\frac{1}{2} \sum_i \frac{(\Delta M_{E,i} - \langle \Delta M_{E} \rangle)^2}{\sigma_{\text{IGM},i}^2 + \sigma_{\text{HIG,loc},i}^2 (1 + z_i)^2}.$$  

where $\theta$ is the set of fitting parameters, $d$ is the FRB data, and the sum over $i$ represents the sequence of FRB data in the sample. Constraints on the flat $\Lambda$CDM model parameters are obtained by setting $\Omega_k = 0$ in (3) and $w = -1$ in (6), and then fitting the mock data for $\theta = (\Omega_m, H_0, \Omega_b h^2, \langle \Delta M_{\text{HIG,loc}} \rangle)$. To investigate spatial curvature in the $\Lambda$CDM model, we allow for $\Omega_k \neq 0$ in (3) and include it as an additional fitting parameter. For the dark energy constraints, we consider two model parameterizations with flat spatial geometry. In the first case, we extend to the $wCDM$ model, allowing for $w = \text{const.} = -1$. We set $\Omega_k = 0$ in (3) and $(w_0, w_\tau) = (w, 0)$ in (7), and fit the data for $\theta = (w, \Omega_m, H_0, \Omega_b h^2, \langle \Delta M_{\text{HIG,loc}} \rangle)$. In the second case, we allow for dark energy to vary with time and use the CPL parametrization (7), and thus set $\Omega_k = 0$ in (3), and fit the FRB data for the parameters $\theta = (w_0, w_\tau, \Omega_m, H_0, \Omega_b h^2, \langle \Delta M_{\text{HIG,loc}} \rangle)$. For all the extended models, we fit to the flat $\Lambda$CDM data described in Section 2.2, and examine how close to fiducial values the additional parameters are constrained. This also allows us to easily combine the constraints with existing data, which is consistent with flat $\Lambda$CDM.

We use the Python package emcee (Foreman-Mackey et al. 2013) to determine the posterior distribution for the parameters, and GetDist\footnote{Package available at https://github.com/cmbant/getdist.} for plotting and analysis. When prior

---

7 Planck 2015 covariance matrices and MCMC chains can be found at http://pla.esac.esa.int/pla/#cosmology.
information is included in the analysis, we use the respective covariance matrix provided by the Planck 2015 data release. We thus calculate the priors according to

$$\ln P(\theta) = -\frac{1}{2} \xi C^{-1} \xi,$$

(10)

where \(P(\theta)\) is the prior probability associated with the parameter values \(\theta\), \(C\) is a (square) covariance matrix, and \(\xi = \theta - \theta_{\text{fiducial}}\) is the displacement in parameter space between the relevant parameter values and the fiducial values. To avoid rescaling the CBSH covariance matrix to accommodate for \(\Omega_k\), we set up our code to fit for \(\Omega_b h^2\), which is a primary parameter in the Planck analysis, and thus its covariance is provided.

### 3. Parameter Constraints Forecast

Here we discuss the FRB constraints forecast for the flat \(\Lambda\)CDM model and some simple one- and two-parameter extensions. In all models, when fitting the most optimistic catalog, FRB1, we find that \(H_0\) and \(\Omega_b h^2\) are unconstrained when no prior information about the parameters is included. This is unsurprising, since \(Dm_{\text{IGM}} \propto \Omega_b H_0\). And, as a result, the other cosmological parameters are only very weakly constrained, if at all. In all models, we find that the measurement precision of \(\Omega_m\) is tens of a percent, hardly good enough to be considered a tool for “precision cosmology” at the subpercent level. We thus include the CBSH covariance matrix in our analysis in order to determine if FRBs offer any additional constraining power.

In Figure 1, we plot a compilation of the marginalized 1D posterior probability distributions for the cosmological parameters, obtained from a combination of CBSH constraints and the various mock FRB catalogs listed in Table 1. Black lines indicate the CBSH constraints used in the covariance matrix for calculating the priors, given by Equation (10). The solid red, dotted–dashed blue and dotted green lines indicate the constraints when FRBS is combined with the FRB1, FRB2, and FRB3 catalogs, respectively. The corresponding 2\(\sigma\) confidence intervals are listed in Table 2. We deal with the various cosmological models in turn, below.

#### 3.1. Flat \(\Lambda\)CDM

Including the CBSH covariance matrix gives the combined constraints, CBSH+FRB, shown in the top row of Figure 1. We find that the posteriors for \(H_0\) and \(\Omega_m\) show only a minor improvement over their priors, as can be seen in the second and third columns. The most improved constraint is given by \(\Omega_b h^2 = 0.02235 \pm 0.00021\), which corresponds to an \(\sim 20\%\) reduction in the size of the 2\(\sigma\) confidence interval of the CBSH prior. The source of this improvement can be seen in Figure 2, where it plots constraints in the \(\Omega_m-\Omega_b h^2\) plane. Here we include the CBSH prior for \(H_0\) with the FRB1 analysis, and plot the resulting constraint (gray) with the CBSH constraints (red). The degeneracy directions of the two ellipses are different, and their intersection gives the combined constraint (blue). Thus, given our current knowledge of the \(\Lambda\)CDM parameters and their covariance, DM observations will provide more information on \(\Omega_b h^2\) than the other cosmological parameters.

Constraints derived from a combination of CBSH with the various FRB catalogs, represented by the colored curves in the top row of Figure 1, illustrate the effect of varying the IGM inhomogeneity and sample size. Increasing the IGM inhomogeneity from \(\sigma_{\text{IGM}} = 200\text{ pc cm}^{-3}\) to \(\sigma_{\text{IGM}} = 400\text{ pc cm}^{-3}\) weakens the constraints considerably. The strongest constraint in this case becomes \(\Omega_b h^2 = 0.02227^{+0.00025}_{-0.00025}\), which corresponds to a \(\sim 5\%\) reduction in size of the 2\(\sigma\) interval of the CBSH constraint. Similarly, reducing the sample size to \(N_{\text{FRB}} = 100\), and keeping IGM inhomogeneity low at \(\sigma_{\text{IGM}} = 200\text{ pc cm}^{-3}\) also weakens any improvement offered by FRBS. In this case, we find \(\Omega_b h^2 = 0.02224^{+0.00026}_{-0.00026}\), which is a \(\sim 2\%\) reduction in the size of the CBSH 2\(\sigma\) interval. Clearly one needs many FRB events in order to mitigate the effects of IGM inhomogeneity.

#### 3.2. Extensions beyond Flat \(\Lambda\)CDM

Curvature—When no priors are included, we find that \(\Omega_k\) is unconstrained by FRB observations alone. Even when the CBSH covariance matrix for \(\Omega_m, H_0, \Omega_b h^2\) is included, the constraint on \(\Omega_k\) remains very weak. However, with the full CBSH covariance matrix included, we find \(\Omega_k = -0.0001^{+0.0026}_{-0.0026}\) and \(\Omega_b h^2 = 0.02235^{+0.00020}_{-0.00021}\). This corresponds to a \(\sim 35\%\) reduction in the size of the CBSH 2\(\sigma\) intervals for \(\Omega_b h^2\) and \(\Omega_k\). The source of this improvement is illustrated in Figure 3, where we plot the 2D marginalized constraints in the \(\Omega_b h^2-\Omega_k\) plane. The FRB1 constraints with CBSH covariance for \(\Omega_m, H_0, \Omega_b h^2\) are shown in gray, and the CBSH constraints in red. Its clear that the gray contour very weakly constrains \(\Omega_k\). However, it runs orthogonal to the CBSH constraint, and intersects it in a way that simultaneously improves both the \(\Omega_k\) and \(\Omega_b h^2\) constraints when the data are combined, shown in blue. Posteriors for \(\Omega_m, H_0\) are dominated by their priors, as can be seen in the second row of Figure 1.

Increasing the IGM variance to \(\sigma_{\text{IGM}} = 400\text{ pc cm}^{-3}\) degrades the constraints to \(\Omega_b h^2 = 0.02226^{+0.00026}_{-0.00026}\) and \(\Omega_k = 0.0009^{+0.0032}_{-0.0032}\), which corresponds to a \(\sim 18\%\) reduction in the size of the CBSH 2\(\sigma\) interval. Similarly, reducing the sample size to \(N_{\text{FRB}} = 100\), we find \(\Omega_b h^2 = 0.02220^{+0.00029}_{-0.00029}\) and \(\Omega_k = 0.0017^{+0.0035}_{-0.0035}\), which corresponds to a \(\sim 10\%\) reduction in the size of the CBSH 2\(\sigma\) intervals. Thus, while FRB observations alone do not constrain \(\Omega_k\), they add some constraining power when current parameter covariance is included. As in the flat \(\Lambda\)CDM case, many FRBs are needed to realize this improvement.

Testing Concordance—When the CBSH covariance for \(\Omega_m, H_0, \Omega_b h^2\) is included in the analysis, the resulting 2D marginalized constraint contours are, in all cases, larger than the CBSH ones. A crucial difference between this result and that of Gao et al. (2014) and Zhou et al. (2014), is that the previous authors assumed perfect knowledge of \(H_0\) and \(\Omega_b\), and neglected any contribution from the host galaxy, and thus got a very narrow FRB contour in the \(\omega-\Omega_m\) plane, which they showed would intersect with, and improve, the current constraints. Alas, we find that this is not the case if realistic prior knowledge about \(H_0\) and \(\Omega_b h^2\) is included.

In the third row of Figure 1, we plot the normalized 1D posterior distributions for the \(\omega\)CDM model parameters. For all catalogs listed in Table 1, we find that the posteriors are dominated by their priors, with the exception being \(\Omega_b h^2\). When using the most optimistic catalog, we find...
\( \Omega_b h^2 = 0.02233 \pm 0.00022 \), which corresponds to a \( \sim 20\% \) reduction in the size of the \( 2\sigma \) confidence interval of the CBSH prior. Increasing the IGM variance to \( s_{\text{IGM}} = 400 \text{ pc cm}^{-3} \) weakens this improvement to a few percent. There is no improvement in the \( \Omega_b h^2 \) constraint if the sample size is reduced to \( N = 100 \).

**Dynamical Dark Energy**—The normalized 1D posterior distributions can be seen in the bottom row of Figure 1. With the CBSH covariance included in the FRB1 analysis, we find that all posteriors are dominated by the CBSH priors, with the exception being \( \Omega_b h^2 = 0.02233 \pm 0.00022 \), which corresponds to a \( \sim 20\% \) reduction in the size of the CBSH \( 2\sigma \) interval. As in the \( \omega \text{CDM} \) model, increasing the IGM variance to \( s_{\text{IGM}} = 400 \text{ pc cm}^{-3} \) weakens this improvement to a few percent, and there is no improvement if the sample size is reduced to \( N_{\text{FRB}} = 100 \). Thus, even under our most optimistic assumptions, we find FRB provide no additional information about the nature of dark energy.

**4. Synergy with 21 cm BAO Experiments**

Future 21 cm Intensity Mapping (IM) experiments designed to measure BAO in the distribution of neutral hydrogen, such as HIRAX and CHIME, are expected for numerous FRBs during the course of their observing runs. Since these FRB detections will essentially come for free (although the redshift will require dedicated observations), we aim to determine whether their inclusion in the data analysis might improve the constraint forecasts for the 21 cm IM BAO alone. Here we perform a simultaneous MCMC analysis of the FRB1 catalog with the mock 21 cm IM BAO measurement presented in Witzemann et al. (2017). The mock BAO data is generated for HIRAX, which is a near-future radio interferometer planned to be built in South Africa. It will consist of 1024 6 m dishes, covering the frequency range 400–800 MHz, corresponding to a redshift between 0.8 and 2.5. We assume an integration time of 1 year, and a nonlinear cutoff scale at \( z = 0 \) of \( k_{\text{NL},0} = 0.2 \text{ Mpc}^{-1} \), which evolves with...
Table 2

| Parameter Constraints for Flat ΛCDM and Some One- and Two-parameter Extensions, Namely, ΛCDM with Spatial Curvature, wCDM and w0 H0, CDM |

| Parameter | 95% Limits | CBSH | CBSH+FRB1 | CBSH+FRB2 | CBSH+FRB3 |
|-----------|------------|------|-----------|-----------|-----------|
| 10 Ωm     | 3.09±0.12  | 3.07±0.11 | 3.10±0.12 | 3.11±0.12 |
| H0        | 67.74±0.92 | 67.86±0.80 | 67.66±0.86 | 67.60±0.89 |
| 10 Ωk h²  | 2.230±0.027| 2.235±0.021| 2.227±0.025| 2.224±0.026|
| (DMHG)    | 215±30    |       | 189±50    | 161±50    |
| 10 Ωb h²  | 0.8±0.08  | -0.1±0.06 | 0.9±0.12  | 1.7±0.35  |
| (DMHG)    | 2.228±0.032| 2.235±0.021| 2.226±0.026| 2.220±0.029|
| H0        | 67.9±0.3  | 67.8±0.2  | 67.9±0.3  | 68.0±0.3  |
| Ωm        | 3.0±0.12  | 3.0±0.12  | 3.0±0.12  | 3.0±0.12  |
| w         | -1.019±0.075| -1.012±0.077| -1.020±0.077| -1.020±0.077|
| (DMHG)    | 2.227±0.027| 2.233±0.022| 2.224±0.026| 2.224±0.028|
| 10 H0     | 68.1±0.9  | 68.1±0.9  | 68.1±0.9  | 68.0±0.9  |
| Ωb h²     | 2.225±0.030| 2.233±0.024| 2.223±0.027| 2.220±0.029|
| (DMHG)    | 204±30    |       | 191±50    | 163±50    |
| w0        | -0.95±0.20| -0.98±0.21| -0.96±0.21| -0.96±0.21|
| (DMHG)    | 2.225±0.030| 2.233±0.024| 2.223±0.027| 2.220±0.029|
| 10 H0     | 68.0±0.9  | 68.0±0.9  | 68.0±0.9  | 67.9±0.9  |
| Ωb h²     | 2.225±0.030| 2.233±0.024| 2.223±0.027| 2.220±0.029|
| (DMHG)    | 205±30    |       | 195±50    | 167±50    |

Note. The first column lists the constraints, for each model, obtained from the FRB1 catalog alone, the second column lists the corresponding CBSH constraints, and the third, fourth, and fifth columns list the combined constraints from the various catalogs listed in Table 1.

Figure 2. Flat ΛCDM parameter constraints in the Ωm-Ωb h² plane. Constraints obtained from the FRB1 catalog with a CBSH prior on H0 are shown in gray, the CBSH constraints are shown in red, and the combined constraints are shown in blue. Without including priors, the FRB constraints are very weak, and so have been omitted from this plot.

Figure 3. Non-flat ΛCDM marginalized 2D posterior distribution in the Ωb h²-Ωk plane. FRB constraints, when including CBSH covariance for (Ωm, H0, Ωb h²), are shown in gray. CBSH constraints are shown in red, and the combined constraints are shown in blue. Without including priors, the FRB constraints are very weak, and so have been omitted from this plot.

redshift according to the results from Smith et al. (2003), k_{max} = k_{NL,0}(1 + z)^{2/(2 + n_{s})} with the spectral index n_{s}. We use these specifications and a slightly adapted version of the publicly available code from Bull et al. (2015) to calculate covariance matrices C_{BAO} for the Hubble rate, H, and angular diameter distance, D_{A}, in N = 20 equally spaced frequency bins. We consider correlations between H and D_{A} and assume different bins to be uncorrelated. For the MCMC analysis, the likelihood of
a given set of cosmological parameters is then calculated using these measurements together with the FRB1 catalog, according to
\[
\ln \mathcal{L} = \ln \mathcal{L}_{\text{BAO}} + \ln \mathcal{L}_{\text{FRB}},
\]
where
\[
\ln \mathcal{L}_{\text{BAO}} = -\frac{1}{2} \sum_{j=1}^{N} (\nu_j - \mu_j)^T \mathbf{C}_{\text{BAO}}^{-1} (\nu_j - \mu_j)
\]
and \(\ln \mathcal{L}_{\text{FRB}}\) is given by (9). Further definitions used are \(\nu_j = (\mathcal{D}_k(z_j, \theta), H(z_j, \theta))\) as well as \(\mu_j = (\mathcal{D}_k(z_j, \theta_{\text{fid}}), H(z_j, \theta_{\text{fid}}))\). All priors are flat and identical to the ones used in the FRB analysis.

We find that FRBs add little to the constraints coming from 21 cm BAO alone—they only tend to remove some of the non-Gaussian tails in the BAO posteriors. However, they do add an additional parameter into the fitting process, \(\Omega_b h^2\), which turns out to be the most competitive constraint. We find \(\Omega_b h^2 = 0.02235^{-0.00032}_{+0.00032}\), which is comparable to the current CBSH constraint, and entirely independent. This suggest that, when combined with 21 cm IM BAO measurements, FRBs may provide an intermediate redshift measure of the cosmological baryon density, independent of high-redshift CMB constraints.

5. Conclusions

In this paper, we have investigated how future observations of FRBs might help us to constrain cosmological parameters. By constructing various mock catalogs of FRB observations, and using MCMC techniques, we have forecast constraints for parameters in the flat \(\Lambda\)CDM model, as well as \(\Lambda\)CDM with spatial curvature, flat wCDM, and flat w0wCDM. Since \(D_{\text{IGM}} \propto \Omega_b H_0\), we find that \(\Omega_b h^2\) and \(H_0\) are degenerate, and unconstrained by FRBs observations alone. And, as a result, the other cosmological parameters are very weakly constrained, if at all. In all models considered here, the measurement precision on \(\Omega_m\) is a few tens of percent, when using the most optimistic catalog with no priors. This is an order of magnitude larger than current constraints coming from CBSH. To determine whether FRBs will improve current constraints, we have included in our FRB analysis realistic priors in the form of the CBSH covariance matrix. With this, we showed that \(\Omega_b h^2\) and \(\Omega_k\) are the only two parameters that are better constrained when FRBs are included. All dark energy equation-of-state parameters are poorly constrained by FRBs.

To investigate how sample size and IGM inhomogeneity affect the resulting constraints, we constructed a number of mock catalogs, while varying \(N_{\text{FRB}}\) and \(\sigma_{\text{IGM}}\). We find that the inhomogeneity of the IGM poses a serious challenge to the ability of FRBs to improve current constraints. For all model parameterizations that we have considered here, we find that only the most optimistic FRB catalog gives any appreciable improvement in the current CBSH constraints. For this catalog, we assumed a relatively low DM variance due to the IGM, with \(\sigma_{\text{IGM}} = 200 \text{ pc cm}^{-3}\), and a large number of events, with \(N_{\text{FRB}} = 1000\). Crucially, these events require follow-up observations to acquire redshift information, which would require \(\sim 100\) days of dedicated optical spectroscopic follow-up. Increasing the IGM inhomogeneity to \(\sigma_{\text{IGM}} = 400 \text{ pc cm}^{-3}\), or decreasing the sample size to \(N_{\text{FRB}} = 100\) causes the resulting constraints to be dominated by their priors.

Future 21 cm IM experiments designed to measure the BAO wiggles in the matter power spectrum will provide independent constraints on cosmological parameters at low/intermediate redshifts. While these observations do not constrain \(\Omega_m\), they will provide competitive constraints on \(H_0\) and \(\Omega_m\) (within the \(\Lambda\)CDM model). Since these experiments are expected to detect many FRBs during the course of their observations, we have investigated combining the BAO constraints with FRB data. We find that this produces a constraint on \(\Omega_b h^2\) comparable to the existing one coming from CBSH observations. Thus, this approach may provide a novel low/intermediate redshift probe of the cosmic baryon density, independent of high-redshift CMB data.

The biggest promise of FRB observations seems to be in locating the missing baryons, and not testing concordance or measuring the dark energy equation of state. This may change should one be able to mitigate the effect of IGM variance and the DM contribution from the host galaxy. There are, however, some caveats. We have assumed that \(f_{\text{IGM}}\) is not evolving with time, and its value is known perfectly. We have assumed perfect knowledge of DM properties, and that it can be reliably subtracted from DM, which is not practical as is known from pulsar observations. Also, we have assumed no error in the redshift of the FRBs. Including these additional sources of uncertainty will weaken any constraints we have obtained here.

We thank Jonathan Sievers and Kavilan Moodley for helpful comments. A.W. is funded by a grantholder bursary from the National Research Foundation of South Africa (NRF) Competitive Programme for Rated Researchers (grant No. 91552). A.W. gratefully acknowledges financial support from the Department of Science and Technology and South African Research Chairs Initiative of the NRF. The Dunlap Institute is funded through an endowment established by the David Dunlap family and the University of Toronto. B.M.G. acknowledges the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) through grant RGPIN-2015-05948, and of the Canada Research Chairs program. Y.Z.M. acknowledges the support by NRF (No. 105925). A.W. acknowledges support from the South African Square Kilometre Array Project and NRF. Any opinion, finding, and conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.

Software: emcee (Foreman-Mackey et al. 2013), GetDist (https://github.com/foreman-mackey/getdist).

ORCID iDs
Anthony Walters @ https://orcid.org/0000-0003-1766-9846
B. M. Gaensler @ https://orcid.org/0000-0002-3382-9558

References
Abdalla, B. F., Abdalla, R., Abbott, T. D., et al. 2017, Natur, 551, 85
Anderson, L., Aubourg, É., Bailey, S., et al. 2014, MNRAS, 441, 24
Bandura, K., Addison, G. E., Amiri, M., et al. 2014, Proc. SPIE, 9145, 914522
Becker, G. D., Bolton, J. S., Haehnelt, M. G., & Sargent, W. L. W. 2011, MNRAS, 410, 1096
Beloborodov, A. M. 2017, ApJL, 843, L26
Betoque, M., Kessler, R., Guy, J., et al. 2014, A&A, 568, A22
Beutler, F., Blake, C., Collins, M., et al. 2011, MNRAS, 416, 3017
Bull, P., Ferreira, P. G., Patel, P., & Santos, M. G. 2015, ApJ, 803, 21
Burke-Spolaor, S., & Bannister, K. W. 2014, ApJ, 792, 19
Caleb, M., Flynn, C., Bailes, M., et al. 2017, MNRAS, 468, 3746
Champion, D. J., Petroff, E., Kramer, M., et al. 2016, MNRAS, 460, L30
Chevallier, M., & Polarski, D. 2001, JCAP, 10, 213
Cooke, R. J., Pettini, M., Nollett, K. M., & Jorgenson, R. 2016, ApJ, 830, 148
Cordes, J. M., & Wasserman, I. 2016, MNRAS, 457, 232
Deng, W., & Zhang, B. 2014, ApJL, 783, L35
DES Collaboration, Abbott, T. M. C., & Abdalla, F. B. 2017, arXiv:1708.01530
Dvorkin, I., Vangioni, E., Silk, J., Petitjean, P., & Olive, K. A. 2016, MNRAS, 458, L104
Fialkov, A., & Loeb, A. 2017, ApJL, 846, L27
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Fuller, J., & Ott, C. D. 2015, MNRAS, 450, L71
Gao, H., Li, Z., & Zhang, B. 2014, ApJ, 788, 189
Ghisellini, G. 2017, MNRAS, 465, L30
Ghisellini, G., & Locatelli, N. 2017, arXiv:1708.07507
Gu, W.-M., Dong, Y.-Z., Liu, T., Ma, R., & Wang, J. 2016, ApJL, 823, L28
Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19
Huterer, D., & Shafer, D. L. 2017, arXiv:1709.01091
Joyce, A., Jain, B., Khoury, J., & Trodden, M. 2015, PhR, 568, 1
Kashiyama, K., Ioka, K., & Meszaros, P. 2013, ApJL, 776, L39
Katz, J. I. 2017, MNRAS, 469, L39
Keane, E. F., Johnston, S., Bhandari, S., et al. 2016, Nat, 530, 453
Keane, E. F., Kramer, M., Lyne, A. G., Stappers, B. W., & McLaughlin, M. A. 2011, MNRAS, 415, 3065
Kowalski, M., Rubin, D., Aldering, G., et al. 2008, ApJ, 686, 749
Kumar, P., Lu, W., & Bhattacharya, M. 2017, MNRAS, 468, 2726
Li, M., Li, X.-D., Wang, S., & Wang, Y. 2011, CoTPh, 56, 525
Li, Z., Gao, H., Wang, G.-J., & Zhang, B. 2017, arXiv:1708.06357
Linder, E. V. 2003, PhRvL, 90, 091301
Locatelli, N., & Ghisellini, G. 2017, arXiv:1708.06352
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Sci, 318, 777
Lyubarsky, Y. 2014, MNRAS, 442, L9
Masui, K., Lin, H.-H., Sievers, J., et al. 2015, Nat, 528, 523
Masui, K. W., & Sigurdson, K. 2015, PhRvL, 115, 121301
McQuinn, M. 2014, ApJL, 780, L33
Meiksin, A. A. 2009, RvMP, 81, 1405
Muñoz, J. B., Kovetz, E. D., Dai, L., & Kamionkowski, M. 2016, PhRvL, 117, 091301
Newburgh, L. B., Bandura, K., Bucher, M. A., et al. 2016, Proc. SPIE, 9906, 99065X
Petroff, E., Bailes, M., Barr, E. D., et al. 2015, MNRAS, 447, 246
Petroff, E., Barr, E. D., Jameson, A., et al. 2016, PASA, 33, e045
Petroff, E., Burke-Spolaor, S., Keane, E. F., et al. 2017, MNRAS, 469, 4465
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016a, A&A, 594, A13
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016b, A&A, 594, A14
Rajwade, K. M., & Lorimer, D. R. 2017, MNRAS, 465, 2286
Räsänen, S., Bolejko, K., & Finoguenov, A. 2015, PhRvL, 115, 101301
Ravi, V., Shannon, R. M., Bailes, M., et al. 2016, Sci, 354, 1249
Ravi, V., Shannon, R. M., & Jameson, A. 2015, ApJL, 799, L5
Riess, A. G., Strolger, L.-G., Tonry, J., et al. 2004, ApJ, 607, 665
Riess, A. G., Strolger, L.-G., Casertano, S., et al. 2007, ApJ, 659, 98
Riess, A. G., Macri, L. M., Hoffmann, S. L., et al. 2016, ApJ, 826, 56
Ross, A. J., Samushia, L., Howlett, C., et al. 2015, MNRAS, 449, 835
Shull, J. M., Smith, B. D., & Danforth, C. W. 2012, ApJ, 759, 23
Smith, R. E., Peacock, J. A., Jenkins, A., et al. 2003, MNRAS, 341, 1311
Spitler, L. G., Cordes, J. M., Hessels, J. W. T., et al. 2014, ApJ, 790, 101
Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, ApJL, 834, L7
Thornton, D., Stappers, B., Bailes, M., et al. 2013, Sci, 341, 53
Totani, T. 2013, PASJ, 65, L12
Wang, J.-S., Yang, Y.-P., Wu, X.-F., Dai, Z.-G., & Wang, F.-Y. 2016, ApJL, 822, L7
Wittmann, A., Bull, P., Clarkson, C., et al. 2017, arXiv:1711.02179
Xu, J., & Han, J. L. 2015, RAA, 15, 1629
Yang, Y.-P., & Zhang, B. 2016, ApJL, 830, L31
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Yu, H., & Wang, F. Y. 2017, A&A, 606, A3
Zhang, B. 2014, ApJL, 780, L21
Zhou, B., Li, X., Wang, T., Fan, Y.-Z., & Wei, D.-M. 2014, PhRvD, 89, 107503