Implications of the Scattering Budget for Fast Radio Burst Sources and Applications

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Bio: I am a PhD Candidate working with Jim Cordes and Shami Chatterjee at Cornell. My dissertation focuses primarily on radio observations of plasma extending from the very local interstellar medium (ISM) to the extragalactic source environments of FRBs, and subsequent applications to the study of extreme astrophysical phenomena including compact objects, gravitational waves, and circum/inter-galactic media (CGM/IGM). I am a NASA Outer Heliosphere Guest Investigator on the *Voyager Interstellar Mission*, where I have led the detection of persistent plasma wave emission, enabling continuous electron density measurements in the very local ISM. I am also a Full Member of the NANOGrav Collaboration, where I apply the study of pulsar dispersion and scattering in the Galactic ISM to the astrophysical noise budget for gravitational wave detection with pulsar timing. My work on FRBs spans the use of propagation effects to probe their local environments and host galaxies, to constraints on the distribution and turbulence of plasma in the CGM of the Milky Way and other galaxies. A list of my publications can be found at this stellakochocker.com.

Talk Summary: Scattering plays a critical role in FRB propagation, detection, and subsequent use as astrophysical probes. FRB lines-of-sight (LOSs) are typically divided into a few main components: the Milky Way (ISM and CGM), the IGM, intervening galaxies, and host galaxies (CGM, ISM, and circumsource medium or CSM). Unlike dispersion, scattering is observable as a range of time and frequency-dependent effects (pulse broadening, scintillation, angular broadening), which can be combined to constrain the location(s) of the scattering medium(s) and hence the scattering budget. This method has been applied to localized FRBs and demonstrated that not only is their scattering dominated by their host galaxies and the Milky Way ISM, but also that scattering in the CGM and IGM appears to be negligible (Ocker et al. 2021a, Cordes et al. 2022b). This result alone has a few key implications:

- Detection of scattering from within host galaxies constrains the degree of density fluctuations therein, which provides a metric for comparing the properties of ionized gas in FRB hosts and the Milky Way. The relative scattering contributions of host ISM vs. FRB local environment remains ambiguous in many cases, although scattering time variations have recently been detected from the CSM of one repeating FRB (Ocker et al., under review).
- Scattering from host galaxies can be used to improve the precision of the DM budget and redshift estimation of non-localized sources (Cordes et al. 2022b, Ocker et al. 2022a).
- Multi-phase models of the CGM must reconcile empirical upper limits on FRB scattering through the CGM of the Milky Way and nearby halos with the proposed prevalence and size scales of "cool" (~10^4 K) cloudlets in CGM gas.

Scattering is also an important selection effect in FRB surveys and biases the observed FRB population — based on CHIME/FRB Catalog 1, a significant fraction of FRBs appear to be unobserved by CHIME due to scattering (CHIME/FRB Collaboration 2021, Chawla et al. 2022).

So where and how do these undetected FRBs incur large scattering? The exact amount of scattering from a given medium depends on its inclination relative to the LOS, its electron density distribution, its redshift (and that of the source), and the observing frequency. Generally speaking, host galaxies and the Milky Way may dominate FRB scattering out to redshifts ~1, but as source redshifts increase the amount of scattering from host galaxies is dampened by time dilation, while the number of intervening galaxies increases substantially enough to begin contributing significantly to the total LOS scattering. As such, a significant fraction of high-redshift ($z > 1$) FRBs may be unobserved due to scattering alone, particularly below 1 GHz (Ocker et al. 2022b).

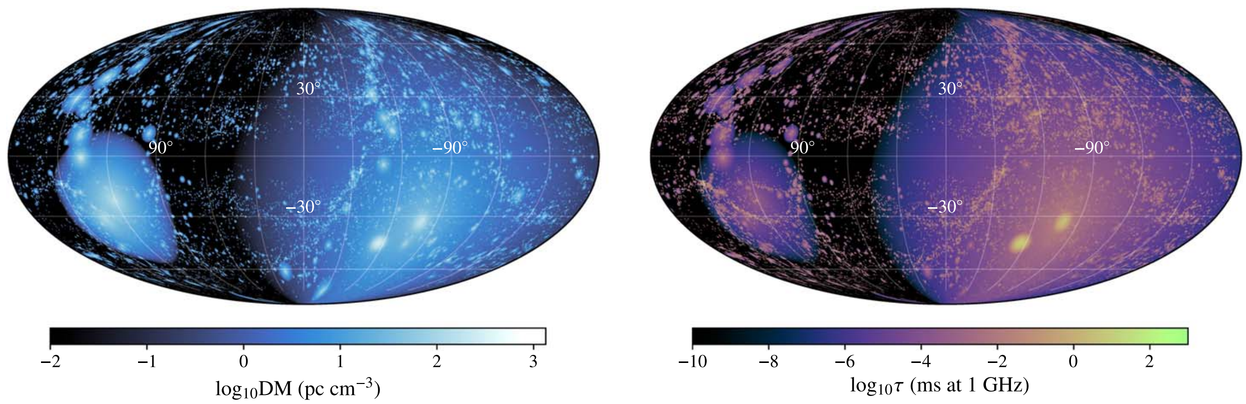

Figure 1. All-sky maps of the predicted DM (left) and scattering time at 1 GHz (right) contributions from galaxies within 100 Mpc, for FRB source redshifts > 0.1. The angular extents of the galaxies' halos were estimated using twice the virial radii and their distances (taken from the Gravitational Wave Galaxy Catalog). Figure from Ocker et al. (2022b).

Given that host galaxies appear to play an important role in FRB scattering for the observed population (largely $z < 1$), studies that aim to constrain FRB progenitor models based on, e.g., their host galaxy properties and source locations need to contend with how scattering (or lack thereof) affects burst detection. If local environments can contribute variable scattering, then the interpretation of scattering from apparent one-off events becomes more ambiguous: the scattering of one burst may not be representative of the local environment as a whole.

Regardless of the degree to which FRBs are unobserved due to scattering, those that are observed enable a number of interesting scattering applications. At low redshift, these applications include:

- FRB DMs, scattering times, and rotation measures can be combined with angular broadening observations of active galactic nuclei (AGNs) to constrain the distribution and turbulent magnetic fields of the CGM in the Local Group. There are now several FRBs and AGNs viewed through the halos of M31 and M33, and there are expected to be many more FRBs detected through these halos in the near future given their large angular extents on the sky.
- Similarly, the Magellanic Clouds cover large angular extents on the sky, and their plasma density distributions remain poorly constrained by their sparsely observed pulsar populations. FRBs detected near and through the Magellanic Clouds will constrain their density distributions and also probe gas bridges and interactions between the Milky Way and these satellite galaxies.
- Very low DM FRBs (i.e., those which do not appear to be extragalactic based on NE2001, YMW16, and/or models of the Milky Way halo) will test the accuracy of Galactic electron density models for the ISM and CGM and serve as input to the next generation of these models. These FRBs (combined with Galactic pulsars) are also the first empirical "rungs" on the FRB DM-distance ladder. With a large enough localized sample, one can imagine a future version of the FRB DM budget that is based on statistical analysis of FRBs across a wide range of DMs and redshifts, as opposed to a highly model-dependent DM budget. Analyses along these lines will ensure that the large, non-localized sample of FRBs does not get left by the wayside after the advent of localization machines like DSA-110/2000 and CHIME outriggers.

I expect that 20 minutes is not sufficient time to cover all of the topics raised in this summary. I am happy to focus on a subset of these topics based on feedback from the conference organizers and session chairs.

References: (1) Ocker, Cordes, & Chatterjee. *ApJ* 911:2. doi:10.3847/1538-4357/abeb6e (2021). (2) Cordes, Ocker, & Chatterjee. *ApJ* 931:88. https://doi.org/10.3847/1538-4357/ac6873 (2022). (3) Ocker, Cordes, Chatterjee et al. *ApJ* 931:87. https://doi.org/10.3847/1538-4357/ac6504 (2022). (4) CHIME/FRB Collaboration. *ApJS* 257:59. doi:10.3847/1538-4365/ac33ab (2021). (5) Chawla et al. *ApJ* 927:35. doi:10.3847/1538-4357/ac49e1 (2022). (6) Ocker, Cordes, Chatterjee, & Gorsuch. *ApJ* 934:71. https://doi.org/10.3847/1538-4357/ac75ba (2022).