Solving Feedback with Electron Power Spectrum Measurements from FRBs

Kiyoshi Masui

Galaxy formation is among the most active areas of research in astrophysics, and the hardest problem in galaxy formation is feedback. Feedback is a catch-all term for processes that regulate or cut-off star formation, with the two dominant forms being supernovae (SN) feedback and active galactic nuclei (AGN) feedback. In SN feedback, the death of newly formed stars inject both thermal energy and momentum into the surrounding gas, heating it, ejecting it from the galaxy and thus removing the fuel for further star formation. Similarly, in AGN feedback, accretion of gas onto super-massive black holes can produce both radiation (that heats surrounding gas or prevents it from cooling) and high-power jets that launch gas over great distances.

Coming to a quantitative understanding of feedback is exceptionally difficult. One reason for this is the complicated and diverse range astrophysical processes involved. Another is the wide range of physical scales—the accretion that powers AGN feedback operates on scales smaller than a parsec, and yet the effects of a single black hole can be felt over distances of megaparsecs. For this reason, feedback cannot be simulated from first principles, and large-scale simulations of galaxy and structure formation must invent "sub-grid" prescriptions that emulate the effects of these processes at the resolution scale.

Furthermore, feedback is poorly constrained observationally. The primary effect of feedback is to heat and eject gas from galaxies, however, the diffuse warm-hot gas in the intergalactic medium (IGM) is difficult to observe directly. As such, sub-grid models must be calibrated to observations of feedback's secondary effects—the impact on star formation rather than the gas distribution. This is, in essence, the missing-baryon problem familiar in the fast radio burst (FRB) field: the exact location of the majority of the universe's baryons can neither be reliably simulated nor directly observed.

Fast radio bursts present a unique opportunity to directly measure the spatial distribution of the IGM, as traced by dispersion-inducing free electrons [1, 2]. Cross-correlating (or stacking) dispersion measurements on foreground galaxy locations provides a measurement of the mean galaxy electron profile. Such an analysis has already been performed by Connor and Ravi [3] for the closest (< 40 Mpc) galaxies and FRBs from the first catalog from the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst (CHIME/FRB) project [4]. This resulted in a measurement of the gas associated with these galaxies on radial scales of ~ 200 kpc.

The analogous measurement performed in Fourier space (which is equivalent in information content) measures the electron–galaxy cross-power spectrum $P_{eg}(k)$ [5]. This quantity is also readily measured in cosmological simulations, making direct comparisons between observations and models straight forward. Simulations implementing different sub-grid feedback models make predictions for the cross-power that differ in amplitude and shape by order unity for wave numbers $0.1\ h/\mathrm{Mpc} < k < 10\ h/\mathrm{Mpc}$. Nicola et al. [6] showed that such statistics are highly informative of feedback physics. Furthermore, opportunities to cross-correlate FRB dispersion with different galaxy sub-samples could provide yet more information. For example, AGN feedback is expected to dominate in the environs of brightest cluster galaxies, whereas SN feedback should dominate in the field. Pessimistically, a precise measurement of $P_{eg}(k)$ will "solve" feedback in the empirical sense—it will provide an observational constraint on functions that are highly sensitive to the sub-grid model. In matching these observations, the model will have little leeway and will thus be fixed. More optimistically, such tight constraints will provide new insight into the underlying astrophysics, solving the problem in a more satisfying way.

Compared to other analyses employing dispersion to study diffuse gas, cross-correlating with galaxies is both highly quantitative (in that it can be compared directly to simulations) and robust to systematics. In other analyses, the ambiguity how much dispersion is contributed by the FRB host (and to a lesser extent the Milky Way) muddies any interpretation. In contrast, in cross-correlation only the dispersion contributed from electrons spatially correlated with the galaxies contribute. Other electron structures add noise, but not bias, which can be overcome with a larger sample.

The observational prospects for this measurement are bright. CHIME/FRB is currently accumulating a sample of hundreds of “baseband” localizations with few-arcminute precision. Such localizations are sufficient to reach the scales of interest (∼Mpc) for foreground galaxies closer than 1 Gpc, corresponding to a redshift range for which there are several galaxy samples to correlate against. In roughly a year, the CHIME/FRB Outriggers project will start producing host associations and source redshifts for CHIME-detected FRBs. This will enable subtraction of the redshift-dependent mean dispersion and remove ambiguity about whether the FRB is in front or behind the galaxy, thus eliminating major sources of noise. Ultimately, Madhavacheril et al. [5] forecast a that a sample such as that to be collected by CHIME/FRB Outriggers will enable better than 10% measurements of $P_{eg}(k)$ over two decades in scale.

About Me

I am an Assistant Professor of Physics at MIT and a member of the CHIME/FRB team. I started my career as a theoretical cosmologist but soon transitioned to observation, working with the hydrogen intensity mapping survey at the Green Bank Telescope (GBT). I became interested in FRBs when (at nearly the same time) I started thinking about using them to map large-scale structure and one was detected in the GBT survey data. That FRB was only the second to be detected at a telescope other than Parkes; the first for which Faraday rotation was measured; and, from the two-screen scattering properties, was the provably extragalactic in the era before direct host associations.

I joined the CHIME team early in its development and have worked on instrumentation and analysis, particularly calibration and statistical inference. I led the deployment of the triggered baseband recording system and have been involved in many of the results coming out of CHIME/FRB, including the first catalog release. I currently spend most my time on the commissioning effort for the CHIME/FRB Outriggers in my role as Project Scientist.

[1] M. McQuinn, Astrophys. J. Lett. **780**, L33 (2014), arXiv:1309.4451 [astro-ph.CO].
[2] K. W. Masui and K. Sigurdson, Phys. Rev. Lett. **115**, 121301 (2015), arXiv:1506.01704 [astro-ph.CO].
[3] L. Connor and V. Ravi, Nature Astronomy, 10.1038/s41550-022-01719-7 (2022).
[4] CHIME/FRB Collaboration et al., ApJS **257**, 59 (2021), arXiv:2106.04352 [astro-ph.HE].
[5] M. S. Madhavacheril et al., Phys. Rev. D **100**, 103532 (2019).
[6] A. Nicola et al., J. Cosmology Astropart. Phys. **2022**, 046 (2022), arXiv:2201.04142 [astro-ph.CO].