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Investigating Cosmic Baryons with Fast Radio Bursts through Simulations and Observations

高速電波バーストを用いたシミュレーションと観測による宇宙バリオンの研究

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Abstract

The distribution of cosmic baryons at low redshift remains one of the central questions in observational cosmology. Although the total baryon density is well constrained by early Universe measurements, a large fraction of baryons is difficult to detect directly at late times because it is expected to reside in diffuse ionized gas in the intergalactic medium (IGM), the circumgalactic medium (CGM), and group- or cluster-scale haloes. Fast radio bursts (FRBs) provide a promising probe of this diffuse baryonic component, because their dispersion measures (DM) trace the integrated free electron column density along the line of sight. However, interpreting the dispersion measure of an individual FRB requires separating contributions from the Milky Way (MW), the diffuse IGM, intervening foreground haloes, and the host galaxy. This thesis investigates the connection between cosmic baryons, FRB dispersion measures, and matter clustering using both cosmological simulations and foreground observations.

On the simulation side, we use the CAMELS-TNG and CAMELS-SIMBA hydrodynamical simulation suites to study how cosmological and astrophysical parameters affect the cosmic dispersion measure distribution $p(\mathrm{DM})$, baryon fractions, and matter power spectra. We compute DM distributions from simulated electron density fields, fit their probability distributions with a parametric form, and train Neural Network (NN) emulators to predict the DM distribution parameters from cosmological and feedback parameters. The emulator successfully recovers the mean DM and scatter of the simulated distributions, while the shape parameters are more difficult to predict because of degeneracies in the fitted probability distribution. We further study the feedback parameter F, which characterizes the scatter of the cosmic DM distribution, and show that its dependence on supernova and AGN feedback is non-trivial. The results indicate that the scatter of FRB DMs is sensitive to baryonic feedback, but also that the limited box size of CAMELS suppresses the contribution from massive haloes and large voids, making direct comparison with observed FRB samples premature.

We also examine the connection between baryonic physics and the matter power spectrum. Using baryon fractions and dark matter power spectrum information as inputs, we train NN to predict hydrodynamical matter power spectra in CAMELS. The results show that baryonic quantities help describe small scale suppression of the matter power spectrum, while information from the corresponding dark matter only simulation improves the prediction by accounting for cosmic variance. This demonstrates that baryon redistribution by feedback leaves measurable signatures in both FRB observables and the matter distribution.

On the observational side, we study the foreground environment of FRB20230907D, a localized FRB with $\mathrm{DM_{obs}} = 1031$ pc cm^{-3} and host redshift $z_{\mathrm{FRB}} \simeq 0.464$. Using Subaru/PFS spectroscopy, supplemented by SDSS redshifts, we construct a foreground galaxy catalog around the FRB sightline. We validate the Nessie friends-of-friends (FOF) group finder using mock catalog, optimize its linking parameters in several redshift bins, and then apply the calibrated group finder to the PFS+SDSS data. The resulting group catalog shows that, beyond the nearby Virgo/M49 foreground environment, only one group intersects the FRB sightline within approximately twice its virial radius. This system lies at $z \simeq 0.09$ and is independently identified as a substantial overdensity in previous SDSS-based group catalogs. After removing a projected secondary component, the cleaned group contains 323 galaxies and has a velocity dispersion of approximately 776 km s^{-1}, corresponding to a cluster scale halo mass of order a few $10^{14}\ M_\odot$ using the Evrard et al. velocity dispersion–mass relation.

We then estimate the DM contribution from this foreground group by modeling it as an ionized halo and integrating the electron density profile along the FRB sightline. Assuming an ionized hot gas fraction $f_{\mathrm{ion}} = 0.90$ and a halo mass uncertainty of 0.3 dex, the $z \simeq 0.09$ group contributes approximately DM $\simeq 150$ pc cm^{-3}. We further calculate the contribution associated with the nearby foreground galaxy UGC 7596 as the residual remaining after subtracting the Milky Way, diffuse-IGM, Virgo, M49 group, $z \simeq 0.09$ group, and host contributions. The non-negative residual assigned to UGC 7596 has a median of approximately 206 pc cm^{-3}, with a central 16–84 percentile interval of approximately 104–295 pc cm^{-3}. This residual should not be interpreted as a direct measurement of the UGC 7596 halo, because it also contains uncertainties in the other foreground and host components.

This thesis shows that FRB dispersion measures are sensitive probes of diffuse baryons, but their interpretation requires both simulation-based modeling and detailed foreground reconstruction. The simulation results demonstrate that baryonic feedback affects the DM distribution and matter power spectrum, while the observational analysis shows that individual FRB sightlines can be strongly affected by identifiable foreground structures. With more localized FRBs combined with wide field spectroscopic surveys, FRBs has been widely used as quantitative probes of the low redshift baryon distribution.

Title: Revealing the Mechanism of Core Formation in Supersonic Turbulence by Three-dimensional Hydrodynamic Numerical Simulation
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Abstract

Prestellar cores are the direct progenitors of stars, yet the roles of supersonic turbulence and self-gravity in setting their formation remain debated. Observations report that cores can be pressure-confined and gravitationally unbound, with separations matching the sonic scale rather than the Jeans length.

We therefore perform three-dimensional hydrodynamic simulations of driven, supersonic isothermal turbulence with the ENZO code, neglecting self-gravity and magnetic fields to isolate the effect of turbulence alone. Three runs in a 3 pc periodic box at a uniform resolution of 1024^3, driven purely solenoidally on large scales, reach saturated rms Mach numbers of $\mathcal{M} = 4.5$, 6 and 8.

Turbulence alone produces abundant core-like density enhancements, whose number increases with Mach number while their masses and mean densities remain largely Mach-independent; only the internal velocity dispersion and the high-mass tail scale with the large-scale flow. These cores are not gravitationally viable: essentially all are pressure-confined ($\alpha_{\mathrm{vir,noG}} < 1$), their internal density contrasts peak a factor of ~ 3 below the critical Bonnor–Ebert value, and their free-fall times exceed their crossing times, so that they would be reshaped by the ambient flow before contraction could proceed. Supersonic turbulence therefore supplies the seeds of fragmentation but not its outcome. The characteristic core separation is ≈ 0.08 pc in all three runs and does not track the sonic scale, though sonic-scale fragments fall below our identification threshold and the question remains open. These results provide a theoretical baseline for interpreting the pressure-confined cores.

Super-resolution Imaging and Spectral Index Research of the Parsec-scale Jet in M87 with EAVN

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Abstract

The limb-brightened morphology resolved in the jets of the nearest active galactic nuclei offers one of the most direct observational windows onto how relativistic jets are collimated, where their radiating particles are energized, and how their magnetic fields are organized in this region. Disentangling the relativistic–geometric and intrinsic contributions to this structure is therefore central to understanding jet formation and propagation. We present a dual-frequency, super-resolution imaging and spectral-index study of the parsec-scale jet in M87, based on eleven paired 22 and 43 GHz epochs observed with the East Asian VLBI Network (EAVN) between 2016 and 2021. Total-intensity images are reconstructed independently with the regularized maximum-likelihood framework `eht-imaging` and the Bayesian framework `Comrade`, and are compared with conventional CLEAN imaging. After angular-resolution matching, image alignment, and frequency-dependent core-shift correction, we construct matched-resolution spectral-index maps for each epoch.

Both forward-modeling methods recover a robust limb-brightened morphology in both bands and across well-sampled epochs, demonstrating that the edge enhancement is a genuine property of the source. The spectral-index maps further reveal a clear *transverse* organization: at fixed projected distance from the core, the limb-brightened edges exhibit systematically flatter spectra than the intervening spine — a spectral limb-flattening that mirrors the total-intensity structure. Relativistic–geometric (Doppler) effects associated with a spine–sheath velocity stratification, already indicated by kinematics, account for part of the total-intensity edge contrast, but cannot by themselves produce a transverse spectral gradient. The spectral limb-flattening therefore requires an intrinsic transverse structure of the radiating plasma, most naturally interpreted as continuous injection of young electrons at the jet edges. From the optically thin spectral index we derive the electron power-law index p, and from the surface brightness we evaluate the characteristic equipartition field B_{eq} — estimated via the minimum-energy field B_{me} — as a quantitative diagnostic of the particle population and emission energy scale across the jet.

These results establish a methodologically robust foundation for probing the transverse structure of the M87 jet with EAVN, and motivate future polarimetric constraints on the true magnetic field, controlled comparisons of imaging algorithms, and multi-frequency imaging as complementary routes to the spectral index.

Keywords: Active galactic nucleus; M87; Jets; Spectral index; Super-resolution imaging; VLBI