

From Cosmic Mystery to Cosmological Probe: Fast Radio Bursts and the Mapping of the Universe

Amit Rao ¹

¹ Center for Scientific Innovation, Hyderabad, Telangana, India

Correspondence: Amit Rao

Abstract

Fast radio bursts (FRBs) were initially studied as enigmatic millisecond-duration radio transients originating at cosmological distances. While determining their physical origins remains an important area of investigation, the scientific significance of FRBs has expanded substantially during the past decade. Increasingly, researchers utilize FRBs not merely as objects of study but as probes of the intervening universe. The dispersion measures of FRBs provide direct information regarding free electrons encountered along their propagation paths, allowing astronomers to investigate diffuse baryonic matter that is otherwise difficult to observe. This review examines the evolution of FRB research from a focus on progenitor identification toward cosmological applications. Attention is given to the role of FRBs in addressing the missing baryon problem, probing the cosmic web, and investigating intergalactic environments. Current limitations and future prospects are discussed. The literature suggests that FRBs are emerging as powerful cosmological instruments whose greatest scientific value may derive from what they reveal about the universe through which they travel.

Keywords: Fast radio bursts; Cosmology; Cosmic web; Intergalactic medium; Missing baryons; Large-scale structure

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1. Introduction

Few astronomical discoveries have evolved as rapidly as fast radio bursts (FRBs). Since their discovery in 2007 [1], FRBs have evolved from an observational mystery into powerful probes of the large-scale universe. FRBs are brief flashes of radio emission lasting only milliseconds yet originating from cosmological distances. Their extraordinary luminosities and apparently diverse observational properties quickly transformed them into one of modern astronomy's most persistent mysteries. Following the initial discovery, subsequent detections established that FRBs represented a genuine astrophysical population rather than an isolated event [2]. As the number of known bursts increased, research concentrated overwhelmingly on a single question: what produces FRBs? Proposed explanations ranged from magnetar flares and compact-object mergers to several other energetic astrophysical mechanisms [3,4]. Subsequent detection of an FRB-like burst from the Galactic magnetar

SGR 1935+2154 provided strong support for magnetar-based models, although questions remain regarding the diversity of FRB progenitors [5].

Although understanding FRB progenitors remains important, recent research has increasingly emphasized what FRBs reveal about the universe through which they propagate. As bursts traverse ionized plasma between their sources and Earth, they accumulate measurable signatures that encode information about intervening matter. Consequently, FRBs have emerged as valuable probes of diffuse cosmic environments.

This review argues that the most significant development in FRB research is not the emergence of a single favored progenitor model but the expansion of FRBs from astrophysical phenomena requiring explanation into cosmological instruments capable of revealing the large-scale structure of the universe. To illustrate this transition, the review first traces the historical evolution of the field before examining how FRBs are increasingly employed to investigate baryonic matter, the cosmic web, and intergalactic environments.

2. From Discovery to Cosmological Instrument

The history of FRB research can be broadly divided into three overlapping phases, summarized in Table 1. The first phase followed the discovery of the Lorimer Burst and focused primarily on establishing whether FRBs represented genuine astrophysical phenomena [1]. Early efforts concentrated on confirming additional events, characterizing burst properties, and determining whether the signals originated within or beyond the Milky Way.

Research Phase	Primary Question	Principal Scientific Goal
Discovery Era (2007–2012)	Are FRBs real astrophysical phenomena?	Confirmation and characterization
Origin Era (2013–2019)	What produces FRBs?	Identification of progenitor mechanisms
Cosmological Era (2020–present)	What can FRBs reveal about the universe?	Investigation of baryons, cosmic structure, and intergalactic environments

A second phase emerged as increasing numbers of FRBs were detected. During this period, the dominant objective was identifying progenitor mechanisms. The discovery of repeating bursts from FRB 121102 challenged catastrophic models requiring destruction of the source and encouraged consideration of multiple progenitor classes. Observational campaigns sought host-galaxy identifications, repeating behavior, polarization properties, and multiwavelength counterparts capable of constraining theoretical models [3].

A third phase developed following major improvements in localization capabilities and the identification of host galaxies. A particularly important milestone was the localization of FRB 180924 to a massive galaxy at cosmological distance [6]. Such observations demonstrated that precise host-galaxy associations and redshift measurements were achievable, opening the possibility of using FRBs as cosmological probes rather than solely as transient phenomena. At the same time, large surveys substantially expanded the known FRB population. The first CHIME/FRB catalog alone reported hundreds of bursts, facilitating population-level analyses that were impossible during the field's early years [7]. Once redshifts became available for increasing numbers of FRBs, researchers recognized that burst signals carried information extending far beyond their origins. In particular, the relationship between dispersion measure and distance offered a means of probing diffuse matter distributed throughout the universe. Landmark studies demonstrated that FRBs could be used to investigate longstanding cosmological questions, including the location of the universe's missing baryons, ordinary matter predicted by cosmological models but not fully accounted for observationally [8]. This

progression illustrates how improvements in localization transformed FRBs from isolated transient events into useful cosmological observables.

3. Dispersion Measures and the Visibility of Cosmic Matter

The transition from astrophysical mystery to cosmological probe is rooted in one key observational property: dispersion measure (DM). Radio waves traveling through ionized plasma experience frequency-dependent delays because lower-frequency waves propagate more slowly than higher-frequency waves. The magnitude of this delay is proportional to the integrated column density of free electrons along the propagation path [4]. For localized FRBs with measured redshifts, the observed DM can be separated into contributions from the Milky Way, the host galaxy, the local source environment, and the intergalactic medium [8].

The importance of this capability becomes apparent when considering the observational limitations of traditional astronomical techniques. Stars, galaxies, and hot gas clouds are detectable because they emit substantial radiation. However, much of the universe's ordinary matter exists as diffuse ionized gas with relatively weak emission signatures. Such material may be difficult to observe directly despite comprising a substantial fraction of the cosmic baryon budget.

FRBs circumvent this limitation because they do not require diffuse gas to emit detectable radiation. Instead, they reveal the cumulative influence of free electrons on propagating radio waves. In effect, each FRB acts as a background beacon illuminating otherwise invisible structures between source and observer.

Dispersion measures transformed FRBs into probes of matter distributed across cosmological distances. Their significance increasingly depends not merely on where they originate, but on everything they encounter during their journey through the universe.

4. Addressing the Missing Baryon Problem

One of the earliest and most influential cosmological applications of FRBs involves the missing baryon problem. Cosmological observations and Big Bang nucleosynthesis models provide precise estimates of the total amount of ordinary matter expected in the universe [9]. In cosmology, this ordinary matter is commonly referred to as baryonic matter and includes familiar constituents such as protons, neutrons, stars, planets, gas, and dust. For decades, however, direct observations of stars, galaxies, and gas clouds accounted for only a portion of the predicted baryonic content.

The discrepancy prompted extensive investigation. Simulations suggested that the missing matter was not truly absent but instead distributed throughout the warm-hot intergalactic medium (WHIM), a low-density network of ionized gas extending along filaments of the cosmic web. Detecting this material directly proved difficult because of its diffuse nature and weak observational signatures [10].

FRBs offered a fundamentally different observational strategy. Rather than attempting to image faint gas directly, astronomers could infer its presence through its effect on radio-wave propagation. Every free electron contributes to the observed dispersion measure, regardless of whether the surrounding gas is bright enough to detect conventionally. A pivotal milestone came when Macquart and colleagues [8] demonstrated the predicted relationship between FRB dispersion measures and redshift. The resulting measurements provided some of the strongest observational evidence to date that a substantial fraction of the universe's missing baryonic matter resides within diffuse intergalactic structures.

Subsequent investigations have refined this picture using larger samples and improved modeling techniques. It was previously demonstrated how localized FRB populations can be used to characterize baryonic distributions statistically [11], while more recent work has begun partitioning baryons among distinct cosmic environments. For example, FRB observations have been combined with galaxy surveys to demonstrate that substantial fractions of previously unresolved baryonic matter can be associated with gaseous structures within the cosmic web [12]. Together, these studies demonstrate a progression from establishing the existence of missing baryons to characterizing their distribution among specific

components of the cosmic web. Independent analyses using localized FRBs similarly concluded that a substantial fraction of the missing baryons reside within the intergalactic medium, further strengthening the emerging consensus [13].

5. Mapping the Cosmic Web

Locating missing baryons establishes that diffuse matter exists where cosmological theory predicts. A more ambitious question concerns how that matter is distributed throughout the universe. This challenge moves beyond baryon accounting and into the broader investigation of large-scale cosmic structure.

The cosmic web consists of interconnected filaments, galaxy clusters, halos, and voids that collectively define the architecture of the universe. Although galaxy surveys reveal the distribution of luminous matter, much of the baryonic content occupies diffuse gaseous environments extending far beyond visible galaxies.

FRBs provide a unique means of probing these structures. Early theoretical work suggested that FRBs could be used to investigate gaseous halos surrounding galaxies, highlighting their potential as probes of baryonic structure beyond visible stellar components [14]. Because dispersion measures accumulate continuously along the line of sight, bursts traversing dense filaments or galaxy clusters should exhibit systematically different properties than those passing through underdense regions. Statistical analyses of sufficiently large FRB samples may therefore reveal how matter is distributed across different cosmic environments.

Recent studies suggest that this possibility is increasingly realistic. Dispersion-measure modeling suggests that FRB observations can distinguish among electron populations associated with galactic halos, filaments, and diffuse intergalactic gas. [15]. Such findings imply that future FRB surveys may contribute to increasingly detailed reconstructions of baryonic structure throughout the universe. As sample sizes expand, FRBs may become an important complement to galaxy surveys and gravitational-lensing studies in efforts to map large-scale matter distributions.

The utility of FRBs extends beyond matter density measurements. Polarized bursts experience Faraday rotation as they propagate through magnetized plasma. Combined measurements of dispersion and rotation provide information regarding both electron density and magnetic field strength. Consequently, FRBs may contribute to investigations of cosmic magnetism, turbulence, and plasma conditions within environments that remain poorly constrained observationally.

6. Current Challenges and Limitations

Despite substantial progress, important challenges remain. One limitation involves uncertainty regarding host-galaxy contributions to observed dispersion measures. Host galaxies vary considerably in structure, star-formation activity, and plasma environments, introducing uncertainty into estimates of intergalactic electron content.

Localization presents a second challenge. Robust cosmological analyses require accurate redshift measurements and reliable host-galaxy identifications. Although facilities such as ASKAP, CHIME, MeerKAT, and the Deep Synoptic Array continue to improve localization capabilities, many detected FRBs remain insufficiently characterized for detailed cosmological applications.

Selection effects also require consideration. Existing surveys operate at different frequencies, sensitivities, and detection thresholds. As a result, observed FRB populations may not accurately represent the underlying burst distribution. Understanding these biases will be necessary before FRBs can be incorporated fully into precision cosmology.

Finally, interpretation depends upon theoretical models describing baryon distributions, feedback processes, halo structure, and cosmic evolution. Continued integration of observational data with cosmological simulations will therefore remain essential for maximizing the scientific value of FRB measurements.

7. Future Directions

The next stage of FRB research is likely to be defined by scale. The publication of the first CHIME/FRB catalog, containing hundreds of bursts, demonstrated the rapid growth of observational capabilities and the transition from individual discoveries to population-level analyses [7]. Future facilities, including DSA-2000 and the Square Kilometre Array, are expected to increase both detection rates and localization precision substantially. Such datasets will transform many current applications from proof-of-concept demonstrations into statistically powerful observational programs.

One emerging objective involves tomographic reconstruction of baryonic structure [15]. Rather than estimating average matter densities, future analyses may generate increasingly detailed three-dimensional maps of diffuse gas throughout the cosmic web. Combining FRB observations with galaxy surveys and numerical simulations could provide unprecedented insight into how ordinary matter is distributed across the universe.

A second frontier concerns cosmic magnetism. Large samples of polarized FRBs may permit reconstruction of magnetic-field properties across galactic halos and intergalactic environments. Such observations could address longstanding questions regarding the origin and evolution of cosmic magnetic fields.

Finally, some researchers have proposed incorporating FRBs into precision cosmology. Improved measurements of dispersion measure–redshift relationships may eventually contribute to independent constraints on cosmological parameters and the expansion history of the universe. Whether FRBs ultimately become precision cosmological probes remains uncertain, but current observational trends suggest substantial potential.

8. Conclusion

Evidence accumulated during the past decade demonstrates that FRBs can help locate missing baryons, investigate matter distributions within the cosmic web, and characterize intergalactic plasma environments. These applications have emerged directly from advances in localization and the recognition that burst propagation encodes valuable cosmological information.

Although significant methodological challenges remain, expanding observational capabilities are likely to enhance the scientific utility of FRBs substantially. The defining contribution of FRBs may therefore be neither the resolution of their origin nor the identification of a single progenitor class, but the transformation of these transient signals into a new observational window on the diffuse matter and large-scale structures that shape the universe.

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