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Fast Radio Bursts as cosmological probes

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Abstract

Fast Radio Bursts (FRBs) are powerful, millisecond duration flashes of radio waves of yet unknown origin. The frequency-dependent dispersion delay imparted on their impulsive signal by the free electrons along their path is well in excess of that expected from the Milky Way Galaxy in the burst direction, stronlgly suggesting an extragalactic origin for these transient events. If this is the case, FRBs can be used as cosmological probes and help solving many open questions such as the location and distribution of the missing baryonic matter in the Universe, the era of Helium reionization, and more.

1 A brief history of FRBs

Fast Radio Bursts (FRBs [1]) are very short, intense flashes of radio waves whose disperion measure, the integrated electron density along the line of sight to the source, is greatly in excess of that predicted (e.g. [2, 3]) for our Galaxy in their direction. Because of that, FRBs are believed to be extragalactic in origin.

The first extragalactic radio burst, known as the Lorimer Burst from the name of its discoverer, was found back in 2007 [4] while searching for extragalactic single pulses from pulsar and Rotating Radio Transients [5] in archival data of the Parkes radio telescope. It was only in 2013, though, that FRBs were recognised as a genuine family of astronomical signals, when four more highly dispersed pulses [1], one of which is shown in Figure 1 (left), were found in the data of the Parkes High Time Resolution Universe Survey [6]. Until then, in fact, despite deep searches in many more archival data and despite repeated observations of the Lorimer Burst location, no further similar signal had been detected (e.g. [7]). In the mean time, again at Parkes, a new type of radio flashes, resembling in many ways the Lorimer Burst were discovered [8]. These transients, however, were clearly local (terrestrial or atmospheric) in origin, being detected at the same time in all 13 beams of the 20-cm multibeam receiver [9] and casted serious doubts on the genuine astrophysical nature of the Lorimer burst. It was later discovered [10] that those strange signals, dubbed Perytons - the name of a mythological animal casting the shadow of a man - were caused by a microwave oven being opened before stopping the timer; Peryton detections, at a closer look, were indeed clustered around lunch time (see Fig. 1, right), and, simultaneously with their 20-cm quasi-dispersed signal, there was a 2.5 GHz signal (in the microwave part of the electromagnetic spectrum!), not present at the time of the genuine FRBs. All remaining doubts were cleared when more transient, dispersed bursts were detected also at telescopes other than Parkes (e.g. [11, 12]).

2 What are FRBs?

The observational characteristics of published Fast Radio Bursts are listed in the on-line catalogue at http://www.frbcat.org [13]. Among the most important ones we cite here:

- the burst dispersion measure: 2 to 200 times larger than the Galactic contribution along the line of sight (covering the range $\sim$ 100-2500 pc/cm^3)

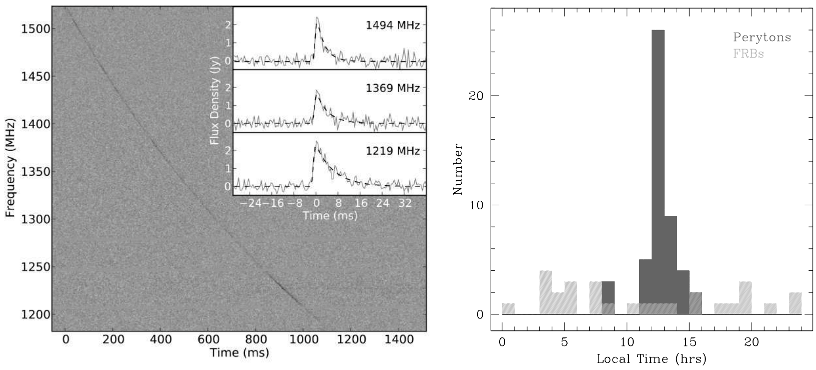

Figure 1: *Left: dynamic spectrum of FRB110220 showing the frequency-dependent time of arrival of the signal, going as ν^{-2} due to the dispersion of radio waves travelling through an ionised medium. In the inset, the frequency-dependent scatter-broadening of the pulse is shown. Right: time of occurrence (in local time) of Perytons (dark gray) and Parkes' FRBs (light grey). The first* [10]*, being produced by a microwave oven, are clustered around lunch time, while the latter, of astrophysical origin, do not show any particular correlation with the time of the day.*

- the burst duration: from a few tenths to a few tens of milliseconds, although most FRBs are not resolved in time because of the dispersion smearing in the single observing frequency channel
- the peak flux density: from 0.04 to 200 Jy, with an average vaue of ~ 23 Jy

In the cases in which it is measureable with high enough accuracy, the dispersion index very precisely matches the value of -2 expected from a radio signal travelling through a cold ionised medium (in Perytons this was not true!). This fact also rules out the possibility that the high DM of FRBs may derive from a dense but close-by environment (e.g. nearby flaring stars, as suggested by [14]), in which the terms beyond the quadratic one, would become important in the DM law [15].

As a further observational clue, pointing towards an extragalactic origin for FRBs, is the fact that, in a dozen bursts, a broadening of the pulse due to scattering is also measured (see e.g. inset of Fig. 1, left panel). Its cause could either be the turbulent inter-galacictic medium (IGM) or an intervening galaxy (e.g. [1]). In the handfull of cases where the scattering index is also measured, it is compatible with the ~ -4.4 value expected from a radio wave travelling through an inhomogeneous, turbulent medium with a Kolmogorof spectrum.

The excess dispersion measure $\mathrm{DM_E}$, i.e. the DM not coming from our Galaxy and its halo, can be ascribed to the intergalactic medium (IGM) and to the host galaxy. The contribution from the latter, however, unless FRBs are produced in the very centre of galaxies, is expected to be small and the DM of the IGM to be the dominant ingredient. From $\mathrm{DM_E}$, hence, assuming a given set of cosmological parameters and a given Universal ionisation fraction, we can derive an estimate of the FRB's redshift z and co-moving distance [16, 17]. Using concordance cosmological parameters, the obtained values of z range from 0.03 [18] to 2.1 [19], corresponding to comoving distances from 128 Mpc to 5.4 Gpc. This, in turn, implies large isotropic emitted energies, up to 10^{40} erg. Another important, although difficult to precisely assess, derived parameter is the birth rate for the FRBs: the most recent estimate, based on the sample of FRBs discovered at the Parkes telescope, is $1.7^{+1.5}_{-0.9} \times 10^3$ events per sky per day, above a fluence of ~ 2 Jy ms [20].

On the basis of these observed and derived characteristics, several authors proposed a large number of possible theories and progenitors for FRBs. Until very recently, when the discovery of 20 new FRBs was announced [18], the number of theoretical models was larger than the number of FRBs themselves! A comprehensive list of proposed theories and progenitors for these transients signals can now be found at https://frbtheorycat.org. Broadly speaking the models can be divided into two main categories: those in which a cataclismic event (a merger, an explosion, etc) is responsible for the production of one single burst of radio emission, and those in which the progenitor is not destroyed and can produce multiple bursts on different time-scales (magnetar flares, giant pulses from pulsars, etc). Despite very extensive follow-up campaigns, only one FRB so far [11] has shown repeated bursts [21], opening the possibility that there may be multiple progenitors for these highly dispersed bursts.

3 FRBs as cosmological probes

Regardles of their specific nature, if they have indeed a cosmological origin FRBs could have a large number of applications. We have mentioned above that we can link FRBs DMs to their redshifts "assuming a given set of cosmological parameters". Reversing the reasoning, if we independently measure the redshift of FRBs host galaxies, we can, through their DM, put constraints on cosmological parameters. One such application is, for instance, the detection of (the ionised part of) the missing baryonic matter in the Universe [22, 23]: all of the ionised gas along the line of sight, including that not directy observed, but inferred by CMB observations (i.e. the '"missing baryons"), concurs to the dispersion of the radio signal and can be hence measured through the dispersive effect. The barionic mass energy density parameter Ω_b enters, indeed, in the equation linking z to DM [16, 17]: localising and measuring the redshift for a few hundreds of FRBs would hence allow us to measure Ω_b [24] and to understand whether the missing baryons lie in fact in the IGM.

With a much larger sample of localised FRBs (10^4), one could also study the probability density function of the DM as a function of redshift and understand how baryons are distributed with respect to galaxy halos (wether closely following them or on different scales); this, in turn, is an important ingredient to understand galaxy accretion and feedback mechanisms [24]. Studying how the DM varies with z for a large sample of FRBs up to high redshifts, can also probe the era of He reionization (EoR) expected between z 3 and 4. At the EoR we indeed expect an observable variation in the steepnes of the DM-z relation [25].

4 Localising FRBs: current and future efforts

In order to undesrtand what FRBs are and to fully exploit them as cosmological probes, it is now clear that we need to find, localise and measure the redshift for many hundreds, or even thousands, of them.

So far only FRB 121102 [11], thanks to its repeated bursts, has been firmly localised in a dwarf irregular galaxy at $z = 0.2$ [26] through radio interferometric observations. Another possible way to find the host galaxy to an FRB, without the need to use arrays of telescopes to get high angular resoultion directly in the radio band, is to detect FRBs in real time and trigger observations at other wavelengths to search for an associated transient event (e.g. a supernova, a magnetar flare, a gamma-ray burst, a gravitational wave...). The SUrvey for Pulsars and Extragalactic Radio Bursts SUPERB [27], an experiment using the 13-beam 20-cm receiver [9] at the Parkes radio telescope to search for pulsars and fast transients, does exactly this: though an on-line GPU pipeline it searches for FRBs in real time sending e-mail alerts to the SUPERB team. The SUPERB pipeline is now widely used at Parkes in piggy-back along with most other pulsar observations. Thanks to this, more than a dozen FRBs have now been detected in real time and multiwavelength campaigns have followed for many of them (e.g. [28, 29, 30, 20]). None so far has revealed a transient event that could be firmly associated to the FRB itself, putting, however, some interesting limit on the possible progenitors.

The Parkes telescope, to date, has been the most succesful in finding FRBs, with a score of 27 discoveries, but new telescopes have recently, or will in the near future, enter the game with new capabilities and technologies, opening new perspectives to the field. The Australian Square Kilometre Array Pathfinder ASKAP [31], for instance, as mentioned above, has recently found 23 new bright FRBs [32] (with an average peak flux density 4 times higher than that of Parkes' FRBs), and the Canadian Hidrogen Intensity Mapping Experiment CHIME [33], who started observations a few months ago, has detected at least one FRB at low frequencies already [34] and promises to find several per day. Both these instruments, despite their different configurations — ASKAP is an array of 12-m dishes equipped with Phased Array Feeds, while CHIME is a transit telescope — have a large field of view, a crucial ingredient to catch fast transients such as FRBs, which can occur at any time in any patch of the sky.

The next step forward will be to also have an high angular resolution (Parkes, ASKAP and CHIME all have tens of arcminutes resolutions), to allow us a direct localization of the FRBs and the subsequent detection of their host galaxies. One of the new instruments that will deploy this capability is MeerKAT [35], the South African precursor of the SKA, whose observations will start in the next months. MeerKAT has an angular resolution of $0.52'$ over a $1.27°$ field of view, providing a much better precision to identify FRBs host galaxies, and is expected to detect hundreds of new fast transients in the next 5 years [36].

On a longer time-scale, the Square Kilometre Array SKA will certainly be the most important instrument for fast transient science, putting together a large collecting area, a large field of view and a high angular resolution, and promising to solve the FRB mystery and to allow to exploit these fascinating, powerfull flashes of radio waves as cosmological probes [37].

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