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AN OVERVIEW OF FAST RADIO BURSTS

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RESUMEN

Presento una breve descripción del estado actual del conocimiento de las fulguraciones rápidas de orígen cósmico detectadas en radio frecuencias en años recientes. Se trata de eventos episódicos de producción de radio ondas que duran alrededor de 1 ms. Su origen parece ser extragaláctico. En este artículo resumo la evidencia que apoya esta afirmación y discuto algunos modelos propuestos a la fecha para explicar la naturaleza de estos acontecimientos.

ABSTRACT

I offer a short review of the current understanding of fast radio bursts: episodic flares of radio waves detected at low frequencies with durations of about 1 ms. These events seem to have an extragalactic origin. I summarize the evidence supporting this statement and I discuss some of the theoretical models proposed so far to explain their nature.

Key Words: acceleration of particles — radiation mechanisms: non-thermal — relativistic processes — turbulence

1. INTRODUCTION

Fast radio bursts (FRBs) are transient flashes of cosmic radio waves with durations of a few ms that are detected at cm-wavelengths. The first event was discovered by Lorimer et al. (2007) using archival data from a pulsar survey at 1.4 GHz from 2001. The identification was possible because of the large dispersion measure (DM) of the event, which showed a quadratic frequency dependent delay, suggesting dispersion of the signal through a cold plasma. The event occurred in the direction of the Magellanic clouds. The Galactic DM from this line of sight is estimated to be of 25 cm^{-3} pc, whereas the FRB presented DM= 375 cm^{-3} pc. The largest DM of a pulsar in the Small Magellanic Cloud is of 205 cm^{-3} pc. Hence, whatever caused the FRB is thought to be behind this galaxy, with un upper limit of $z \sim 0.3$. The duration of the event was 5 ms, with a flux density of 30 ± 10 Jy. It was a single spike, with no repetition. Subsequent monitoring of the region showed no further events in the DM range of 0 to 500 cm^{-3} pc.

Since Lorimer et al.'s discovery, about 20 FRBs have been detected, most of them by Parkes radio telescope (see the list in the FRBCAT: Petroff et al. 2016[3]). A repeating FRB has been also found with Arecibo 305-m telescope in Puerto Rico (Spitler et al. 2016) and a counterpart for this source was recently detected (Chatterjee et al. 2017). If these bursts occur, as everything indicates, at cosmological distances, then they are the most luminous radio events in the known universe. Dedicated instruments are under construction with the aim of increasing the number of detections. In the meanwhile, the ultimate nature of these events remains an utter mystery. In what follows I will review the main facts and the current best ideas about FRBs and their origin.

2. FACTS

The DM is defined as the integrated column density of free electrons along the light of sight to a source:

$$\text{DM} = \int_0^d n_e dl. \tag{1}$$

The radiation of an extragalactic source pass through the ionized gas of the interstellar (ISM) and the intergalactic medium (IGM), where the free electrons make the group velocity of the signal frequency dependent. Higher radio frequency radiation arrives, then, before the radiation emitted at the same time but lower frequencies from the source. All observed FRBs show a dispersion delay $\delta t \propto \text{DM}\ \nu^{-2}$. This is in agreement with the effects of a cold plasma, suggesting an effect of the IGM. The DM obtained for FRBs are in the range 375-1600 cm^{-3} pc which correspond to distances of 0.5-4 Gpc in a FLRW metric,

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[3]The catalogue is available on-line at http://www.astronomy.swin.edu.au/pulsar/frbcat/.

assuming a dispersion in the host galaxy of the burst of 100 cm^{-3} pc.

The fluxes of the FRBs are in the range 0.1-30 Jy, implying a huge energy release per burst of the order of $10^{38} - 10^{40}$ erg. The event rate of the bursts has been estimated to be $\sim 10^4$ sky^{-1} day^{-1} (Thornton et al. 2013). This means that FRBs are more frequent than gamma-ray bursts.

A real time discovery of a FRBs was first made by Ravi et al. (2015) with the Parkes telescope. No repetition was observed in subsequent runs. Another real time event was detected by Petroff et al. (2015). No repetition was observed in this case either, despite extensive searches. But Petroff et al. succeeded in the determination of all four Stokes parameters. The burst's emission was circularly polarized at 21 ± 7 % (3σ), but no linear polarization was present above 1σ (10 %). The observed polarization is not necessarily intrinsic to the event; it might be induced by scintillation during propagation of the signal.

FRBs are dubbed upon the date of detection according to the convention: FRB YYMMDD. FRB 121102 is the only one known to repeat so far. All bursts associated with the original detection share a consistent DM and sky localization (Spitler et al. 2016, Scholz et al. 2016). The individual bursts have fluxes in the range 0.02-0.3 Jy, with no indication of periodic behaviour. The bursts, however, seem to cluster in time forming short sequences of events. Chatterjee et al. (2017) achieved the sub-arc second localization of FRB 121102 using high-time-resolution radio interferometric observations that directly imaged the bursts. They found that the bursts occurred very close to a faint 180-μJy persistent radio source with non-thermal emission and a faint optical counterpart. This latter optical source has been identified by Tendulkar et al. (2017) as a low-metallicity, star-forming, dwarf galaxy at a redshift of z = 0.19274, corresponding to a luminosity distance of 972 Mpc. Further insights on the persistent radio source were provided by Marcote et al. (2017) through very-long-baseline radio interferometric observations with the European VLBI Network and the 305-m Arecibo telescope. They were able to simultaneously detect and localize the bursts and the persistent radio source on milliarcsecond scales. The bursts are consistent with the location of the steady source within a projected linear separation of less than 40 pc.

The fact that no repetitions similar to those of FRB 121102 has been observed in other bursts despite extensive searches strongly suggests that there might be two different kind of progenitors producing the events. One should survive the flares in order repeat. The other type might be of catastrophic nature. Stringent constraints to any kind of source, however, come from the very short timescales that are characteristic of the phenomenon.

3. ORIGINS

The extremely rapid variability of FRBs ($\delta t \sim$ 1 ms) is indicative of relativistic beaming, so the linear size of the source would be $\delta x < c\Gamma^2\delta t$, where Γ is the Lorentz factor of the radio emitter that is moving towards the observer. The brightness temperatures associated with such compact and bright sources are extremely high: $T_{\rm b} > 10^{36}\Gamma^{-2}$ K (Luan & Goldrich 2014, Katz 2014). This is many orders of magnitude above the Compton limit for incoherent synchrotron radiation. A coherent origin of the radiation, then, seems to be unquestionable.

Additional constraints on the source can be obtained if we assume that the ultimate origin of the radiation is magnetic. A lower limit on the magnetic field that sets the particle flow in motion is $B^2 > 10^{19}\Gamma^{-3}(\delta t/1\mathrm{ms})^{-3}$ (Katz 2014). Even in case of large beaming, FRBs seem to be produced by compact objects of stellar origin with strong magnetic fields such as neutron stars, magnetars, or gamma-ray bursts (GRBs).

An alternative to FRB production in extremely relativistic sources has been proposed by Loeb, Shvartzvald, & Maoz (2014). These authors suggested that FRBs might be rare eruptions of flaring main-sequence stars within $\sim$1 kpc. Rather than associating their excess DM with the intergalactic medium, they relate it to a blanket of coronal plasma around their host star. However, this scenario seems to be ruled out by free-free absorption that limits a stellar corona's DM to be well below that of FRBs (Luan & Goldreich 2014). With the recent identification of a host galaxy, the cosmological origin of FRBs seems secured. In the next section I will review some of the mechanisms that have been proposed to account for these events.

4. MECHANISMS

Mechanisms for FRBs can be divided in two broad groups: those of catastrophic nature where the source does not survive the production of the bursts, and those which repeat. The energy budget is similar in both cases, at the level of 10^{42} erg s^{-1}.

A popular model was proposed by Falcke & Rezzolla (2014): a heavy neutron star in a metastable equilibrium undergoes collapse to a black hole. The

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magnetic field of the star, once the event horizon is formed, is detached from its source and must reconnect at the speed of light, sweeping the magnetosphere of the star and producing a coherent radio pulse. A variation of this model is a Kerr-Newman black hole with a charged magnetosphere (Liu et al. 2016). The magnetosphere is unstable and when subjected to strong perturbations collapses into the black hole, which suddenly discharges. With t the discharge the Kerr-Newman black hole becomes a pure Kerr black hole and the non-hair theorems hold: the source of the exterior magnetic field disappears and a massive reconnection event occurs, with the consequent electromagnetic pulse. A similar version has been proposed by Zhang (2016). This type of models, where the emission is triggered by a massive reconnection event, are generically known as 'blitzars'.

Models where the source survives the flaring event allow for repetition. Lyubarsky (2014) proposed that the bursts might be synchrotron maser emission from relativistic, magnetized shocks in magnetars. At the onset of the magnetar flare, a strongly magnetized pulse is formed, which propagates away through the relativistic magnetar wind and eventually reaches the nebula inflated by the wind within the surrounding medium. The radio bursts could be generated at shocks formed via the interaction of the magnetic pulse with the plasma within the nebula. In a recent communication, Lyutikov (2017) as argued that the localization of the FRB 121102 at $\sim$ 1 Gpc excludes a rotationally-powered type of radio emission. Despite of this, magnetars might be responsible of other events, since it is far from clear how many populations of FRBs there are.

A quite different type of model has been proposed by Dai et al. (2016), who suggested that repeating FRBs might result from highly magnetized pulsars traveling through the asteroid belts of other stars. A repeating FRB could originate from such a pulsar encountering a large number of asteroids in the belt. During each pulsar-asteroid impact, an electric field induced outside of the asteroid has such a large component parallel to the stellar magnetic field that electrons are torn off the asteroidal surface and accelerated to ultra-relativistic energies almost instantaneously. The subsequent movement of these electrons along magnetic field lines causes coherent curvature radiation. This model, however, is difficult to reconcile with the energy demands of FRB 121102, whose distance is now well constraint.

A more conservative approach based on well-established lab physics has been proposed by Romero et al. (2016). The interaction of a relativistic electron beam with a target made out of plasma results, through plasma instabilities, in the generation of strong turbulence. This induced turbulence can be characterized as an ensemble of soliton-like wave packets, called cavitons. Cavitons result from an equilibrium between the total pressure and the ponderomotive force, which causes a separation of electrons and ions. The cavity is then filled by a strong electrostatic field. This effect has been verified both in the lab (Robinson 1997) and through numerical simulations (Sircombe 2005). Electrons passing through a caviton will radiate because they are accelerated by the electrostatic field, launching a broadband electromagnetic wave packet. The final result is a Bremsstrahlung-type of radiation of coherent nature. There exist different astrophysical scenarios where this mechanism might occur. The most obvious situation is that of a cloud been irradiated by the inner jet of an AGN. In a forthcoming paper, Vieyro et al. (2017) apply this mechanism to the host galaxy of FRB 121102. Repetition is simply explained by multiple interactions with several clouds. Another possible scenario suggested by Romero et al. (2016) is the jet of a GRBs interacting with the clumps of the progenitor star's wind.

Very recently, Katz (2017) has proposed a very interesting hypothesis: FRBs would be pulsar lightning. Lightning occurs in an electrified insulating atmosphere when a conducting path is created by and permits current flow. FRBs may occur in neutron star magnetospheres whose plasma is divided by vacuum gaps. Vacuum is a perfect insulator unless electric fields are sufficient for electron-positron pair production by curvature radiation, a high-energy analogue of electrostatic breakdown in an insulating gas. FRBs may be in this way "electrars" powered by the release of stored electrostatic energy.

There are several other models proposed so far for FRBs. More than 200 paper have appeared on FRBs since their discovery. This means more than 10 papers per known event! It is impossible to review them all here. Whatever is producing FRBs, it seems to be the result of a fast release of electromagnetic energy in a very small spatial region, likely not greater than 10-20 km.

5. PROSPECTS

FRBs might be very useful in measuring the geometry of the Universe. This is because the DMs contain information on the cosmological distance the photons of the bursts have traveled, which provides constraints to the parameters that characterize the universe (Hilmarsson 2015). Type Ia SNe are good cosmology probes, but cannot be detected to very high redshifts. DM measurements from FRBs at a redshift $z \geq 3$ would constitute a unique probe of the early universe . FRBs can thus help to constrain the equation of state of the so-called dark energy, since in some models the parameter w in $p = w\rho$ deviates from -1 and evolves with redshift.

Because the IGM is inhomogeneous, the assumption of a simple homogeneous IGM to predict the relation between DM and redshift for individual FRBs might deviate from what it actually is. By detecting sufficient FRBs along various sight lines, within a narrow redshift range, e.g. $z \sim 0.05$, the mean of observed DMs would not be subjected to such a problem. The mean DM caused by the inhomogeneous IGM should be comparable with the accuracy of the luminosity distance measurement with SN Ia, i.e. 10%. This could make FRBs a viable cosmic probe.

Acquiring spectroscopic measurements of FRB afterglows is currently a challenge because of the poor positional constraints of FRBs obtained from single dish telescopes, and the apparently faint afterglows. Luckily, in the coming years there will be radio transient surveys conducted by radio interferometers such as the square kilometer array (SKA). With a wider FOV and higher sensitivity, the SKA will survey the sky at a much faster rate than current telescopes, and is expected to discover and precisely localize plenty more FRBs. A plethora of FRBs can then be expected to be observed, adding further constraints on the IGM (Zhou et al. 2014).

Any step into the knowledge of the nature of FRBs requires a dramatic increase in the number of detections. So far, most FRBs have been detected by the Parkes radio telescope. The limited angular resolution of this instrument means that it is very difficult to localize the progenitor, unless the FRB repeats. The next step toward understanding FRBs lies in detecting more events using a range of instruments and, most importantly, localizing the events for identification purposes. A range of experiments have been performed or are underway to meet this challenge. There is a growing awareness of the impact the new generation of low frequency radio telescopes may be able to make in further understanding FRBs. Efforts are being put into observational programs at frequencies below 1 GHz, for example using the Square Kilometre Array Molonglo Prototype (SKAMP), and the Murchison Widefield Array (MWA). About 30 telescopes are looking for FRBs nowadays, and dedicated searches are increasing. The Canadian Hydrogen Intensity Mapping Experiment (CHIME), a radio telescope in Canada that should start hunting for FRBs later this year, might see as many as a dozen a day. CHIME comprises four 100-metre-long, semi-cylindrical antennas, which lie near the town of Penticton in British Columbia (Castelvecchi 2015). But detection is not enough to solve the mystery. Coordinated multifrequency observations are necessary to pinpoint host and progenitors. The next few years promise to be a very exciting period for the astrophysics of extreme events.

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