Notes on Astrophysical Transients

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i. Introduction

We are going to talk about transients that **happen once** and at **cosmological distances**.

The discovery of GRBs is a very interesting story: it starts with a treaty signed between Soviet Union and US in 1963 to ban the nuclear tests in the atmosphere of Earth. At time no one trusted each other, so US launched the Vela satellites to catch gamma rays in case the Soviet Union would test nuclear weapons. These would have given traces in gamma rays that these satellites would detect.
They didn't detect weapons but GRBs. This discovery was first published in 1973. Some years passed between detection and publication because it took time to understand that these are astrophysical sources: sources of short gamma ray flashes that come from different parts of the sky with huge uncertainty on the localization. It was unclear what was the astrophysical source of these gamma ray pulses, but it was clear they were not artificial.
The first GRB was discovered on July 2, 1967 (published in 1973). It's a lightcurve in gamma rays, in the range of MeV, transient with a second variability.

Where this kind if transients predicted? Actually there is a paper by Colgate who predicted short gamma ray pulses a few months before the real discovery of GRBs. This was justified as shock break out emission from stellar explosions. He did several mistakes in the paper that by chance allowed him to reach GeV range and therefore by chance he predicted these gamma ray flashes. Now we know that shock break out emission cannot produce GRBs but it was really close.
Moreover, it is probable that this paper was written to justify scientifically the Vela satellites.

Where are these gamma ray pulses coming from? We have a paper from 1975 analyzing all possible proposed theories to explain GRBs: it can be Jupiter, antimatter, BH in binaries, unconventional stars. With a limited information on GRBs alone without localization and distance it was impossible to make more precise theories.
The main problem is measuring distances to objects. If we are assume they are galactic sources their energy would be 10^{40}erg and this could be explained in different ways. If we assume cosmological distances, then the energetics would huge and never before have we observed something similar.
The genius of the time, **Paczynski**, assumed what if GRBs are coming from cosmological distances. He showed that this is possible because the energy released in GRBs is comparable with stellar rest mass energy and so in some kind of death of stars this could be the case. It was not so popular at the time.

ii. First observations: BATSE and BeppoSAX

People needed ore observations and there was the launch of a new instrument BATSE in 1991 to detect more GRBs and to localize them better then Vela satellites. BATSE is a very wide field of view instrument and can catch a GRBs from wherever it comes in the sky. Its energy range is between 20keV and 2MeV. It found many GRBs: a few per week (now we detect them on a daily basis).
If we look at the distribution we immediately notice that there is no a preferred place from where GRBs come and this was the first hint that they are not galactic sources. If they were we would have them concentrated in the disk of the galaxy.

Another interesting thing in astrophysics is to plot $\log(N)$ vs $\log(S)$. This is a way to understand the distribution of sources in space. S is the fluence[1] of the astrophysical transient and N is the number. From this one realizes that GRBs should come from very large distances.

[1]**Fluence** is the total energy released by a gamma ray burst during its active gamma ray. This corresponds to the flux integrated over the duration of the burst, and rages over three orders of magnitude, from apporximately 10^{-8} to 10^{-3} erg/cm^2

There can be many reasons why GRBs are isotropically distributed in the sky. The next instrument was BeppoSAX, launched in 1992, and the difference wrt BATSE, is that BeppoSAX also had a wide field X ray camera on board. This means that while we detect the gamma ray burst by itself, which is now called the **prompt emission**, we can also follow it up in X rays. The X ray camera allowed to detect long lasting emission associated with the GRB, which is called **afterglow** and lasts for days. The afterglow is something monotonically decaying. The association of the afterglow to the prompt emission allowed the localization, because in X rays we can localize much better. It also allowed to follow up it from the ground in all the other bands. The follow up allowed to discover the host galaxy. We can measure the galaxy redshift and from this we understood that they were located at cosmological distances.

III. GRB progenitors

In one second we observed an energy that would require the Sun all its life to emit. It is clear that this should be a very violent process, stellar death or the birth of a new object. Among the many theories proposed earlier two remained:

- GRBs originate from the coalescence of compact objects
- GRBs originate from core collapse of massive stars, above $20M_{\odot}$

In both cases we have predictions to check. In the case of compact objects we expect gravitational waves. In the case of core collapse it's a bit easier, because then at later times we expect to see a supernova.

On the other hand, there was an interesting discovery: if we look at the histogram of total duration of GRBs (we use the T_{90}, which is the time during which we accumulate 90% of photons), we can see that there is a bimodal distribution: short and long duration.
Also the hardness ratio (how hard is the spectrum of GRBs, we divide the amount of photons in the hard energy range by the amount of photons in the soft energy range) and we see that short GRBs are harder and long GRBs are softer. This was obtained only looking at the prompt emission and it is indicating that there could be two progenitors for these events.
All the theory squeezed to two kind of progenitors:

- Short GRBs linked to NS mergers, because we have less mass remained after the merger. Therefore, less mass less energy and the GRB will be shorter.
- Long GRBs linked to massive stars, for which we have more mass in the accretion disk.

People assumed that after a merger or a collapse we form a new object, most probably a BH, and we have some amount of matter remaining and becoming an accretion disk.

IV. Jet launch mechanism

There have also been proposed mechanisms to launch the jet. The **central engine** is the one producing the jet: it's the newborn object which is launching the GRB (it could either be a BH or a NS). There are two classical mechanisms to launch the jet:

- The **Blandford-Znajek mechanism** where we convert the spin of the BH to the magnetic jet. It is required that the magnetic field in the accretion disk is toroidal. If we accumulate a lot of magnetic field in the vicinity of the BH, we can transfer the momentum of the BH to the extraction of magnetic field energy in a collimated form. This mechanism is very promising because the efficiency of extraction of the momentum from the BH is very large and we can in principle we can reach kinetic energies of order of 10^{51}erg/s. The collimation is due to the fact that energy can only go out in the direction perpendicular to momentum.
- **Neutrino driven jets**: in the vicinity of a BH the temperatures are so high that we have neutrinos, which annihilation provides electron-positrons pairs in a specific direction that looks like a jet. The outflow of pairs is created in polar directions, because we are limited in a very small region around the BH where this neutrino

production is effective. That's why we have collimated pairs. In this case the process is less efficient that the previous one.

It is really hard to find out which is the actual mechanism, also because the information on the jet is lost meanwhile it propagates. One of the most promising methods uses NS mergers. Here we can actually from GW analysis we can have an idea on which amount of mass has remained in the accretion disk. We can have a conversion factor between the energy in the jet and the accretion disk.
There is also a way of producing outflows from **millisecond magnetars** that are objects we have never seen but that could exist and that could also be the central engine of a GRB.
For the long GRBs (duration > 2s) the confirmation of a SN was done in 1998. At late time a color dependent bump appears and looking at its spectra we find that it is a SN.
For short GRB we had to wait till 2017 when we detected the gravitational signal of binary NS merger and then 2s after a short and weak GRB.

v. Relation to host galaxies

There is also a way to study the progenitors of GRBs by looking at their host galaxies. Before GWs and finding SN, people simply looked at host galaxies and at the position of GRBs in their host galaxies. For short GRBs only a few galaxies were detected and they were typically early type (elliptical galaxies, where we expect to have NSs and where we do not expect star formation and massive stars). For long GRBs they were found in galaxies with high star formation where we can have massive stars.

If we look at the distribution of redshifts for GRBs we see that they are also at $z \sim 9$. They are so energetic that the flux limits of our instruments allow to see it. We could see them up to $z \sim 20$, but at such high redshift the gamma rays become X rays and we don't have a wide field of view in the X ray to detect them. So GRBs could exist at the very end of the Universe and to detect them we need softer instruments on which we are already working.
The average redshift is around 2, which is consistent with the peak of star formation in the Universe. We have huge energies up to 10^{52}erg. If we look at the **variability**, we have many lightcurves for different GRBs and they are all very different. From lightcurves we can learn the minimum variability timescale which can help us understand physics. If the total duration is up to thousand seconds, the variability ranges from milliseconds to 1s. By variability we mean the shortest pulse.

Looking at the spectrum of GRBs: we can take the spectrum for all the duration or we can take the spectrum for one spike. They are very similar. We can study the number of photons or the νF_ν representation where we have flux. Te spectrum is very simple: there are no spectral features, there are no spectral lines, it's a simple two power laws.

vi. The requirement of relativistic motion

So we observe an energy of 10^{52}erg for a variability scale of 10^2. Automatically we can estimate the optical depth: we want to know if what we observe we could observe it. We need the size of the emitting region and the energetics. The dominating thing that can trap gamma rays from escaping to us is the gamma rays annihilation. If gamma rays have an energy comparable to the rest mass of electron then the gamma rays can produce electron-positron pairs. There is a danger of annihilation here, because the energy is huge and all is put in a small box of 10^8cm, which is simply the speed of light to the variability (the light crossing path). If we put all these photons in such a small box we find that the optical depth is huge, $\tau_{\gamma\gamma} = 10^{10}$, so that we would not see the GRB. It would just remain there. The elegant way to reduce these ten orders is to introduce **relativistic motion**: the emitting sphere is moving with almost the speed light and this can reduce the ten orders.
By introducing relativistic motion we increase the radius of the emission by four orders and we can have an idea

about where these gamma rays are produced (now they are no longer gamma rays because if they are boosted they are not gamma rays in their comoving frame. Whatever emits the GRB moves with a huge Lorentz factor $\Gamma \sim 100$ (outflow velocity ~ 0.99c).

So we have a theory that predicts ultra-relativistic motion of gamma rays and now we have to confirm it. We have to measure the velocity of the outflow. One way is to look at the afterglow which lasts longer and comes from the same outflow. We can look at it i all the bands. If the GRB is very nearby, which is once per year, we ca look at the radio band in two different ways:

- One is a very exotic way and was done in 1997: people noticed that these scintillations actually are larger with time. We can have an idea how the emitting surface of the afterglow is expanding with time and therefore have an idea of the velocity.
- If the GRB is very close, $z \sim 0.5$, (VLBI observations: build a huge radio telescope by putting many small telescopes around the world), we try to measure the size of the emitting region in radio. Having bigger telescopes we can resolve better. It's a really difficult task as it requires $10-20$ telescopes in different countries. If we wait a bit, say 50 days after the GRB, this will expand a lot since it's moving relativistically and we can hope to detect the image. It has been done and it was found the angular size. The source has to move relativistically otherwise it cannot expand so much in a such a short timescale. This was another confirmation of ultra-relativistic motion associated with a GRB.

Now we have to look at the model. If we start with a NS or BH we end up with a **fireball**, i.e. a soup made of pairs and photons. Something which is opaque. The firts model was proposed by Reese and Paczynski where we have a fireball expanding under its own pressure, gets to relativistic velocities and when at a certain moment becomes transparent we see the GRB. The central engine is producing a fireball, which is expanding and accelerating at relativistic velocities. At a certain moment it becomes optically thin and whatever was there, which was previously in equilibrium with pairs, goes out to us. This predicts a **thermal spectrum**, but we have two power laws. We need non thermal emission: we need to accelerate particles on the distances comparable to the transparency radius and then emit them.
We need somehow to kill the thermal emission, which we do not see, in a way that we get that energy back to the particle we are going to accelerate in order to produce non thermal spectrum.
In 1990 there was a proposal by Shemi and Piran to add baryons in the jet: if we put protons in the fireball, once the fireball expands most of the energy will not remain there but it will be given to protons, therefore to the kinetic energy of the jet because protons are massive and carry a lot of energy. Instead of having all the energy of the fireball in the thermal emission, which we don't see, we give it to protons and so we save it for later. Then we dissipate it again giving it to the internal energy of particles that are going to emit non thermally.
We can imagine a fireball with protons. At the end of the evolution of the fireball we simply have a shell where most of the kinetic energy is in protons and it's not emitting anything. We have a plasma shell with relativistic velocity, then it becomes transparent at 10^{10}cm or something, it reaches relativistic velocities, still does not emit and we a have a proton-electron shell.
The central engine will produce many fireballs because the accretion disk is something made of many clouds. We can dissipate the fireball in two different ways. If the engine is producing shells with different Lorentz factors, they collide and dissipate their relative kinetic energy. We can also interact with the ISM. We'll have shocks.
The external shock cannot explain the GRB, the prompt emission, simply due to variability. We need internal dissipation: internal shocks (collision of different shells) or most of the energy of the jet is in the magnetic field and we can dissipate it before feeling the ISM thanks to magnetic reconnection. The prompt emission physics is more uncertain.
The afterglow physics is simpler: it's a shock propagating in an external medium and accelerating particles in the external medium, electrons and then they emit via synchrotron.

VII. Is it a jet?

How do we know if it is really a jet? We do not see images of it. To see that it is really a jet we can look at the afterglow emission. In the afterglow we have external shock that dissipates energy gradually when it moves and accumulates more and more matter of the external medium. So the velocity of the shock will decrease with time. In the beginning when the velocity is large, the emission is beamed (we do not if it is a jet or not as we see only a small part of it). When the Lorentz factor drops significantly we start to see all the image that makes the lightcurve and therefore if it is jet then we will have a really fast drop in the flux. This drop has been observed and it is achromatic (the same in all energy bands as it should be because it is not an effect of the spectrum but simply of geometry). This is called **jet break time**: it allows to measure the opening angle of the jet.
There are also other ways, less model dependent.

VIII. GRB correlations

There are two famous correlations related with GRBs:

- **Amati correlation**: correlation between the total energy[2] and the peak energy of the GRB in the rest frame. This is a correlation between the position of the peak of the spectrum and the total integral of the spectrum. This is not observed in other transients
- **Ghirlanda correlation**: the same but with the true energy (correct for the opening angle of the GRB). It is tighter.

These correlations are still not explained, but they would allow to do cosmology. If have this relation for GRBs we can measure distance and redshift thanks to this relation. This is good as it allows to go to really high redshifts.

IX. Observational results

Another interesting observable was seen in 2004 with Swift. This is an all in one instruments. Swift changed the field. Before Swift era we could model the afterglow emission by this model of external dissipation. But Swift found new features in the X ray afterglow, which were not present before due to instrumentation. It found a steep decay phase starting after the GRB which is much steeper wrt to any prediction of external shock model. The second feature is a **plateay phase**, which is flat, flatter than any shock model can give us. It also found many **flares**, that are very surprising: we expect a GR to be finished in 4 hundred seconds. But GRB like pulse s appear at late time: there is still central active engine, which is very difficult to have with a BH (some people use these flares to claim a **magnetar**).

In 2008 Fermi satellite was launched. It was another epoch when we started to detect GeV emission related to GRBs. Here we have to count photon by photon. We also see more afterglows in GeV. This helped to constrain the physics of acceleration in afterglows.

In 2019 MAGIC detected TeV emission from a GRB for the first time. A TeV energy was a big surprise. A few months after HESS also detected sub-TeV. It's related to inverse-Compton emission.

We have a huge hope for CTA, which will be much more sensitive than MAGIC. Since TeV is absorbed in intergalactic medium, having transients producing in TeV can help do a lot of interesting physics.

[2] We talk about the **isotropic equivalent energy**, assuming that we have a sphere. Its simply flux multiplied by $4\pi d^2$, but we know it is a jet so the true energy is smaller.

II. Stellar explosions

i. Reconstructing the full picture: systems forming long GRBs

Let's imagine a collapse of massive star with the possibility to launch a jet: we want to see how the whole system looks like. Before we were discussing separately the gamma ray burst part which is only the jet, or we were discussing the shock breakout part, or the propagation of jet. Now let's take the whole system together.
We have a collapse of a massive star, it has an envelope that remains there with some density profile and then we create a jet. We have a birth of a, most probably, BH and an accretion disk and from this system we hope to have the jet which should propagate not in vacuum as we discussed so far but in the star's envelope. We can have two situations:

- The jet successfully breaks out and survives after the propagation of the ejecta
- Choked jet: the jet dies and we won't have a GRB

ii. Successful jet

Let's look at the numerical simulations which study this kind of propagation of the jet in the ejecta for the case of a star envelope. We see the first second of propagation: we notice an interesting thing called the **cocoon** which is an outflow that we are creating and it is the result of the propagation of the jet in a dense medium. While the jet propagates in the envelope it will throw away the matter on the sides, therefore it will create more wide angle outflows, less relativistic, which are called cocoon.
So we have the jet and a very broad and less energetic outflow being the cocoon. So the final product is not a narrow jet with some opening angle, but it's an entire system with structure: we have the largest Lorentz factor in the center and then an outflow with decreasing velocities on the sides. The cocoon is simply the effect of something propagating very fast in a dense medium. This is of course the case of a successful jet.

iii. Choked jet

When the central engine, i.e. the system with the BH and the accretion disk, is not active for a long enough time then the jet will die in the ejecta (envelope). We'll have instabilities that will kill the jet. However, even if we do not have the jet we'll still have the cocoon. In this case we will have the shock breakout from the cocoon. In the case of successful jet we can also have shock breakout from the cocoon on the sides, and also the shock breakout from the jet. In the case of choked jet we do not have a GRB, we do not have a free jet that survives when at later times we create a GRB and an afterglow. In this case we will only end up with a shock breakout signal.
At very late times, for a choked jet, the cocoon is surviving and expanding with sub-relativistic velocities ($\Gamma \sim 2-3$). It still propagates and can also create an afterglow. But this will be a GRB-less system.

iv. Cocoon

Actually at very early times the SN emission can be absorbed by the material of the cocoon, because the light is not propagating in vacuum but in the cocoon ejecta. Therefore, at very early time when the cocoon is still very dense, we can have an effect on the SN by the fact that we have a cocoon, by the fact that SN light will propagate through the cocoon before reaching us. Since the cocoon is much faster than the SN output, the absorption features will be very broad because of the cocoon very large velocities.
One of the methods to study the cocoon, to claim its existence, is to catch early SN emission. If we are perfectly on-axis and looking at the jet we cannot see the effect of the cocoon. If we are slightly off-axis, the GRB can be a faint but we can actually see the SN light that has passed through the cocoon and will' have broad absorption lines. We can actually manifest the cocoon existence. This was discovered in 2019 by very detailed optical observations. It was a really nearby source and we were very sensitive to the light of the system. The optical emission is not

dominated by the afterglow and we can see the very early SN emission which probably passed through the cocoon. The detailed spectroscopy of this emission showed very broad spectral lines confirming the passage through the cocoon. So we can see the presence of a cocoon in long GRBs observed slightly off-axis.

v. Compact binary coalescences

We have the coalescence of compact systems like NS-NS and NS and not so massive BH. In the case of NSBH we can have a chance that something survives after the coalescence. In the case of BNSs it is also not so clear if in all cases or some of the case for a give EOS something survives.
We have some channels where we create stable or metastable NS or BH with some matter that remains bounded with the central object and we potentially can have a jet. That is short GRBs were thought to originate from this kind of systems, simply because we have much less mass in the accretion disk than in the case of core collapse and so the GRB will be fainter and the central engine will work for less time and we'll have a short GRB.

In this kind of systems we also will have an environment where the jet will propagate. If we take two NSs the first ejecta will be in the equatorial plane. This is called **dynamical ejecta** and it is made before the merger, in the inspiral phase. In the inspiral phase some amount of matter is dynamically ejected in the equatorial plane. We will use the **electron fraction**, which represents the amount of neutrons in the ejecta. Some amount of matter remains bounded and it forms the accretion disk and the central engine.
We have also other ejecta, prior to the launch of the jet:

- Ejecta from the **disk wind**, because if the luminosity if the luminosity of the accretion disk is large enough it can blow away some amount of matter
- **Polar ejecta** due to the shock created when we have the final collision between the NSs: some matter will be thrown away in the polar directions

The composition of all possible ejecta in all possible directions is very complex and it is different for different systems. If take a NSBH we won't have polar ejecta because we don't have the shocks due to colliding NSs.
Other important parameters are the **velocity of the ejecta** that we have prior to the launch of the jet and the electron fraction.

Once again we will have the propagation of the jet not in vacuum but in these specific ejecta that we have. For some amount of time we can also have magnetars before it collapses to a BH (it could also be a stable magnetic providing a continuous polar injection).

vi. Nucleosynthesis of heavy elements

All these parameters of the ejecta, velocity, mass and electron fraction, are dependent on the systems (NS or BH). It's easier to constrain from observations. It is important because from the ejecta of NS mergers there will be nucleosynthesis of heavy elements. If we have many free neutrons we will synthesize heavy elements. There will be two different regimes. If we compare the timescale of the beta decay and the timescale of injection of free neutrons, we can have either that we are able to bombard the nuclei faster than the nuclei beta decay or the opposite

- The rapid **r-process**: the bombarding time of the nuclei is much shorter than the β decay time. This is very important because we can synthesize very heavy nuclei
- The slow **s-process**

We ask to be able to produce the majority of the periodic table elements. The Big Bang produced the lightest elements. Up to iron we can produce them in the stars. For the heavier ones we need more energetic process: we need free neutrons. It can be either SN ejecta or NS merger ejecta.

The process of nucleosynthesis is very fast. It starts with the capture of first neutrons until we fill all the heavy nuclei which decay to stable elements. We need to have enough low electron fraction of the system.

It was in 1994 that it was first proposed that r-process could happen from BH-NS mergers. Thanks to the discovery of binary pulsars (confirmation that in nature there could be BNSs). Then we also observed short GRBs. The most important work is the work by Le and Paczynski in 1998 where they asked the question of what is the EM signature of BNSs merger. They proposed that even if we have ejecta with a small mass like $10^{-2} - 10^{-3} M_{\odot}$ (which is nothing compared to a SN where we have few solar masses), we can actually observe the optical signal of this system when it becomes transparent. The difference is that it is more difficult to model wrt the SN signature, because we have very complex opacity profiles.

vii. Kilonova models

The next important work was in 2010 by Metzger who actually understood that the electron fraction in ejecta in various regions can be very different. In the equatorial plane the electron fraction is much smaller because it is not affected by neutrinos, which typically go in the polar directions and they would increase the electron faction. Therefore, in the polar direction we won't reach the synthesis of very heavy nuclei, but this will make the opacity smaller in the polar direction. So in the polar direction we will have a brighter, earlier and bluer kilonova, while from the equatorial plane, since its opacity will be large because neutrinos will not increase the electron fraction and the amount of neutrons will be huge, the transparency of the output will be later, therefore fainter and therefore redder. In 2013 two independent works confirmed the presence of a near IR, so redder kilonova, for a GRB at a later time. Then we had the famous kilonova GW170817.

For the Le and Paczynski theory we have to compare the diffusion velocity with the velocity of our outflow for which we have an idea (fraction of speed of light). Having the mass and velocity of our outflow we can predict when our ejecta will become transparent.
The difficulty in kilonova models is **opacity**. We have to imagine a system with many nuclei. We have to have an idea of the transition lines of all the nuclei which will define the opacity: we need to know the exact composition of the outflow, which is very difficult. That is why people try to approximate opacity.

Let's summarize all the outflows and all the possible EM signatures. We will have the red kilonova peaking at much later time ($2-3$days), the blue kilonova which will be earlier and brighter (the matter around the central engine is very hot and that is why we have neutrinos and secondly we can have for some amount of time a meta-stable NS that can contribute to the neutrino emission). Then we have the cocoon, which is shock breakout. If we have a successful jet this jet will make the GRB and then the afterglow. We will have an afterglow also from the cocoon, but it will be less bright and we still haven't observed. We will also have an afterglow at very late times (10 days or even more) form the kilonova ejecta: not bright at all and in the radio band because it is not a relativistic afterglow. So we have the two component kilonova.

viii. GW170817

Let's discuss the GW emission from BNSs and the short faint GRB which happened 2s after. The short GRB we have seen is 3 orders of magnitude fainter than we expected. It's a bit weird.
We have three proposed scenarios:

- We have a uniform jet without wings and we see it off-axis. This is a bit difficult, because off-axis we won't see the GRB itself as the Doppler will be small and the photons will annihilate rather than being observed.
- The jet has a structure and we see it off-axis. That is why the GRB is less luminous.
- This is not a GRB but a shock breakout emission

The first possibility is excluded, but the second and third are still valid.
The kilonova emission was amazing. The afterglow emission is very interesting, it peaked hundred days after the merger of the BNS. This is very different from all the other afterglows we saw which peaked from hundreds seconds, not days. The only way to reproduce this result is to see a structured jet off-axis. If we were observing a top head jet, we will not have the rising part in the afterglow when we observe it off-axis. If we have a structured jet we can explain the power law rising part of the afterglow.
There was this amazing follow up in the radio bands with VLBI observations. The only wide field telescopes that we have nowadays is the gamma ray ones and so we can detect GRBs only if we observe them on axis, or at most 1° off-axis. In other bands the probability of observing something off-axis is very small.
Seeing GW170817 we were able to observe the signatures of everything: kilonova outflows and jet production with a structure. It is difficult to explain the rising part if we do not have a structure.

III. Fast radio bursts

i. Historic introduction

They were predicted by chance by Colgate. There was a prediction of short radio pulses due to the birth a NS when we have a collapse of a star. When we have a NS we create a megnetosphere and it will be young and we can have a coherent emission from the electrons moving in the magnetic fields of the magnetosphere. So there was a prediction of short radio pulses, potentially FRBs.

There also was an amazing work by Martin Reese suggesting the explosion of mini BHs. If we imagine to have very light BHs in the beginning of the Universe, $10^{-17} - 10^{-18} M_{\odot}$, due to Hawking radiation they will finish their evaporation today. The last stage of evaporation will give a burst, an explosion and this can give a light in some wavelength, which Reese argued to be in radio wavelengths. Later it was understood that it would possibly be a gamma ray flash. Until now people search for this kind of signals from evaporating BHs.

Motivated by these theoretical predictions, people were doing searches for millisecond radio pulses in 1979, but they did not find any.

ii. Major discoveries in radio bands

In 1967 PhD student Jocelyn Bell discovered repeating radio pulses now called pulsars. These are NS with beams pointing at Earth.
1974 there was the discovery of a binary NS, one of which was a pulsar. The period changes completely in agreement with GR. If we assume the binary loses energy due to emission of GWs, we can predict the change of the period of a pulsar and it perfectly matches the GR predictions. It is an indirect confirmation of GWs.

The next major discovery in the radio band is in 2007. Before the Lorimer paper, people were writing pipelines to find periodic signals in radio bands, but no one was searching for single radio pulses. However, in 2007 Lorimer was searching for **single radio pulses** in the archive of data and he found an amazing source from 2002. It was found a single pulse with a **huge dispersion**. The signal is also **much brighter** than that of a pulsar. So these signals are definitely not pulsars but a new transient called fast radio burst.
Since it was the detection of a single pulse, by a single instrument and by a single group: we needed confirmation that it wasn't a fake signal. The first discovery of a single millisecond burst is called of extragalactic origin because of the huge dispersion. It was discovered by "the dish", the Parkes observatory in Australia.
The first FRB was not taken seriously from the beginning because of its large dispersion, because it is too bright, and it was a single event. Furthermore, there is the microwave oven story according to which they were detecting a series of radio pulses at lunch time. They needed more discoveries from independent instruments. These confirmations came from analyzing more and more data and now we have a lot of FRBs, confirmed by other radio observatories.

iii. FRB distance

If we look at the sky distribution, we see that FRBs are not concentrated in the galactic plane and there is a bias towards observing the southern sky (because most of the radio telescopes are in Australia).
The usual questions are if the sources are galactic or extragalactic and whether we have emissions in other wavelengths, the so called afterglows. Are these pulses repetitive? What are the progenitors?

Let's discuss the distance. The dispersion is huge: if we compare it to that of pulsars, the difference of arrival times between two bands is proportional to the inverse of the square of the frequency of the radio waves. The dispersion measure is the product between the density of free electrons and distance. We can either have a very

dense material and the FRB sitting in the galaxy, or we can have a normal ISM or inter-galactic medium but the source is located very far. In both cases we can have very large dispersion relations, because free electron density and distance are degenerate, we cannot distinguish between one another.
If compare the dispersion measure with the galactic latitude, we see that at higher latitudes the dispersion relation of usual radio transients decreases because there is less dense matter. However, for FRBs it is huge and it does not depend on galactic latitude. This is the first hint that FRBs are extragalactic sources, because they need large distances in order to accumulate this large dispersion measurements.
However, there were also models explaining the large dispersion measurements by having a very large density gas around the progenitor of FRBs. Now these models are disfavored.

FRBs are at cosmological distances. For a dispersion measure if 10^3 we get a redshift measure of 1, so these are very far sources. Here dispersion is calculated considering intergalactic medium.

iv. Spectral analysis

If we take the luminosity density of all possible transients versus frequency, we see that FRBs lie in the most extreme place of coherent radiation. If we compute the brightness temperature (the temperature a source with a given flux will have) this will be huge, of order of 10^{36}K. We cannot create this huge temperature for a transient using usual thermal processes. In order to have so large temperature we need a collective and instantaneous emission: maser kind of emission or collective curvature emission where all the particles move along a magnetic field and emit simultaneously.

v. Propagation effects

There will be several propagation effects, related to propagation in the dense matter around the progenitor in the host galaxy, in the intergalactic medium and then in our galaxy. In the case of our galaxy it is simpler because we have an idea of the matter distribution in our galaxy. In the intergalactic medium we can assume something, at least the evolution of density versus redshift. For the host galaxy we can know something if we know the type of the host galaxy. The only missing part is the environment around the progenitor of the FRB, which we can constrain by assuming everything else.

Since it is a radio wave we will have reflection, diffraction due to matter alongside the FRB and us. We will have a broadening of the pulse. To see the initial pulse we need to de-disperse it, and decompress it for the effects of scintillation. These are model dependent and no so accurate procedures, but this will allow us to see the pulse as it is produced. The scattering of radio waves is frequency dependent. At smaller frequencies we will have broader pulses. We will also have a delay.
We have three effects:

1. Delay
2. Broadening of pulses with smaller frequency
3. Spectral spikes due to scintillations

These effects should all be accounted for in order to reconstruct how a real FRB should look like.
There is also a Faraday rotation, the rotation of polarization angles which is also frequency dependent. If we measure the change of polarization angle, we can have a clue about the magnetic field alongside the propagation. If we have both the rotation and the dispersion measure we can in principle have an idea of the magnetic field. This will be linked to the progenitors. This was done for a specif FRB.
The rotation measure is huge for only one FRB, called 121102 and it's order 10^5. When we convert it to the magnetic field it will be order of 10mG, which is huge. This is supporting of having as a central engine for FRB a NS. This FRB 121102 is a repeating FRB.

VI. Rates

Imagine to take every instrument we have and observe all the sky and we detect some amount of FRBs. We can so estimate the rate of FRBs: now we have a rate of order of thousands. If we convert it to cosmological rate, it would be of order of 10^{-5} per year per galaxy, which is smaller than the rate of SN. So there is no strong claim that SN and FRB are always associated, but it can be also an effect of beaming.
We still haven't observed the afterglow associated with a FRB. We observed several host galaxies, which can tell us a lot, mainly about progenitors.

VII. FRB 121102

It is the first repeating FRB, discovered in 2016 from analyzing archive data. Before, all FRB were thought to be single events. By repeating we mean simply that we see other pulses, but it is not a periodic signal like in pulsars. All the pulses are different, there is no specific repetition trends. The localization is not so good, but we can claim that these pulses belong to the same FRB, because the dispersion is exactly the same for all of them.

We have seen many single FRBs and some repeating and until now it is not very clear if there are two classes of sources, the repeating and the single ones, or if it is the same thing and we do not see the repetition because we have to wait a lot or we miss it. People think there are two classes of sources.
The host galaxy of 121102 was found at redshift 0.19 and it was a dwarf galaxy. It didn't help to understand the nature of FRBs. It was just a confirmation of extragalactic origin.

VIII. Modeling FRBs

The fact that we have radio pulses, single or repeating, is most likely associated with NSs because we already know how to produce them there. A single NS would have a single pulse, if we have some very strange NS that is in the phase of producing FRBs. Other models are related to AGNs, cosmic strings, and also to aliens.
Avi Loeb actually wrote a paper about single FRBs as signals from aliens. Interestingly, when he computed a possible signal from a Dyson sphere, he discovered that it should be in radio.

The last discovery on FRB was in April 2020, where an association of a FRB with a soft gamma ray repeater in our galaxy was discovered. A soft gamma ray repeater is believed to be a magnetar. These are X ray transients thought to originate from magnetar quakes and we can have a hard X ray flash.
Integral is a gamma ray instrument. If we look at the lightcurve of a soft gamma ray repeater, we see like three peaks, and for the first two we have the coincidence with a FRB. This is an incredible match that some of the FRBs can originate from single NSs in a specific phase of their life.