ALMA MATER STUDIORUM · UNIVERSITÀ DI BOLOGNA

SCUOLA DI SCIENZE
Corso di Laurea in Astronomia
Dipartimento di Fisica e Astronomia

SYNCHROTRON EMISSION AND ASTROPHYSICAL APPLICATIONS

Tesi di Laurea in Astronomia

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Abstract

Il sincrotrone è uno dei principali processi radiativi astrofisici. Questo tipo di emissione è dovuta al moto di particelle cariche, prevalentemente elettroni, che si muovono a velocità relativistiche dentro un campo magnetico. Il fenomeno si verifica su diverse scale ed è influenzato solamente dall'energia delle particelle cariche e dall'intensità del campo magnetico. Troveremo dunque l'emissione di sincrotrone associata sia ad oggetti compatti, come stelle di neutroni rotanti, sia ad oggetti estremamente estesi, come gli ammassi di galassie.

Contents

Chapter 1

Physical background

OBSERVATIONAL ASTRONOMERS work essentially on the information given by the electromagnetic radiation emitted from astrophysical objects. In order to understand the properties of such objects from the analysis of these types of waves, we must study the mechanisms of energy production.

One of the most significant radiative process is synchrotron emission, that we will be discussing in the following pages.

1.1 Emission from single particle

The trajectory of a charged particle moving in a magnetic field is deflected by the **Lorentz force** that constricts it in a helical path along the magnetic lines of force. As this is an accelerated motion, the particle will radiate following the *Larmor formula*, which is, for relativistic particles

$$P = \frac{dW}{dt} = \frac{2q^2}{3m^2c^3}\gamma^2\left(\frac{d^2\mathbf{p}}{dt^2}\right)^2 \tag{1.1}$$

where $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ is the Lorentz factor, c is the speed of light, q and m are the charge and the mass of the particle respectively. From eq. (1.1) we see that the particles best accelerated are the lightest ones (i.e. electrons and positrons rather than protons) and the power emitted significantly increases for very energetic particles.

The radiation from charges accelerated by magnetic fields in a non relativistic regime is called *cyclotron emission*, but when the velocity is approaching the speed of light, relativistic effects must be considered and *synchrotron radiation* is created.

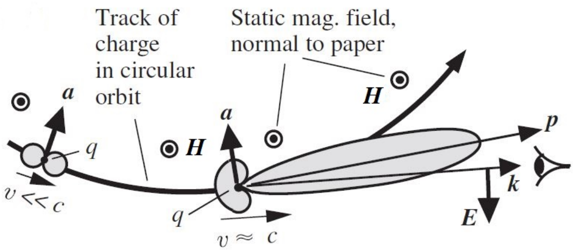

Figure 1.1: The beaming of radiation [Bradt 2008].

When we insert the acceleration due to the Lorentz force for a magnetic field **H**

$$\frac{d\mathbf{p}}{dt} = \frac{q}{c}\mathbf{v} \times \mathbf{H} \tag{1.2}$$

in eq. (1.1), considering an ultra-relativistic ($\beta = \frac{v}{c} \simeq 1$) electron, we obtain the energy loss of the particle

$$(-)\frac{dW}{dt} = \frac{2e^4}{3m_e^2c^3}\beta^2\gamma^2H^2\sin^2\theta = 1.6 \times 10^{-15}\gamma^2H^2\sin^2\theta \tag{1.3}$$

in $erg \cdot s^{-1}$, if H is measured in G. The term $\sin^2\theta$ refers to the angular distribution of the emission. However, *relativistic aberration* changes the classical dipole pattern focusing the beam of radiation in a slender cone of semi-aperture $1/\gamma$, hence the amplificated emission along the instaneus velocity direction (Fig. 1.1).

Relativistic treatment is also required for pulse analysis. The angular gyrofrequency of cyclotron emission $\omega_H = qH/m$ immediately results in the pulse duration $t_{cycl} = 2\pi/\omega_H$. That is not true in synchrotron radiation where *relativistic Doppler effect* shortens the pulse duration by a factor $2\gamma^2$

$$t_{sync} \simeq \frac{1}{\omega_H\gamma^2} \tag{1.4}$$

which, by applying Fourier's analysis, will provide the characteristic frequency of emission[1]

$$\nu_c \simeq \frac{3}{4\pi}\frac{1}{t_{sync}} \approx 4.2 \times 10^{-9}\gamma^2H \tag{1.5}$$

in GHz, if H is measured in μG.

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[1] The full power spectrum of a single electron is more complex and calls upon Bessel function $K_{5/3}$ which is nearly peaked at $0.3\nu_c$ and then decreases esponentially: the emission is almost monochromatic.

1.2 Emission from an ensemble of particles

The emission from a single particle is both illustrative and a simply case, whereas the real case involves an ensemble of particles.
Synchrotron emission is a **non-thermal** process, i.e. the energy spectrum of charged particles doesn't satisfy a *Maxwellian distribution.*

Let us consider a **power law** energy distribution of relativistic electrons

$$N(\varepsilon)d\varepsilon = N_0\varepsilon^{-\delta}d\varepsilon \tag{1.6}$$

where $\varepsilon = \gamma mc^2$ is the energy of a moving particle and N_0 is related to the number density of the particles. Under the assumption that all particles radiate at the characteristic frequency ν_c, the specific emissivity results

$$J_s(\nu) = \frac{dW_s(\nu,\varepsilon)}{dt}N(\varepsilon)\frac{d\varepsilon}{d\nu} \approx N_0 H^{\frac{\delta+1}{2}}\nu^{-\frac{\delta-1}{2}} = N_0 H^{\frac{\delta+1}{2}}\nu^{-\alpha} \tag{1.7}$$

where $\alpha = \frac{\delta-1}{2}$ is called *spectral index* of the synchrotron radiation.

The final spectrum is then interpreted as the superposition of various contributions of each single electron, each one emitting at its own characteristic frequency (Fig. 1.2).

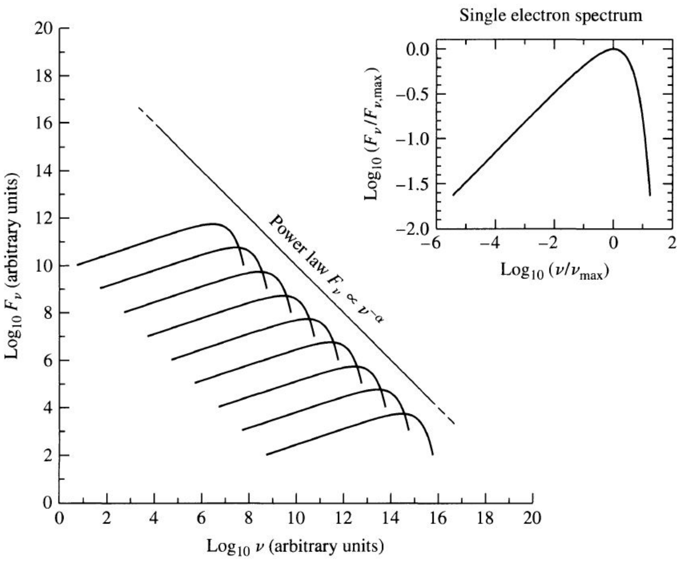

Figure 1.2: The power law spectrum of synchrotron radiation and, at the upper right, the spectrum of a single electron [Carroll & Ostlie 2007].

1.2.1 Acceleration mechanisms

The discovery of synchrotron emission first raised the problem of how can particles be accelerated at relativistic speeds. Now, we will see three mechanisms that can explain the radiation coming from the astrophysical objects we will discuss in Chapter 3.

Fermi mechanism Enrico Fermi proposed a scenario where charges can be accelerated by the collision with a magnetized cloud. The interesting thing about Fermi mechanism is that the population of accelerated particles follows a synchrotron-like power law energy distribution. The energy gain is exponential and the process is aided by high particle velocity and dense clouds. However, the timing of action for this scenario is enormously larger than what has been shown by observations.
Shock waves can make this mechanism more efficient, significantly reducing Fermi's times; this plays an important role in the astrophysical contex.

Oblique rotator model Strong magnetic fields in pulsars povide the acceleration of free electrons. One possibility of pulsar emission's mechanism is the oblique rotator model, proposed at the end of the 60's by Thomas Gold and Franco Pacini. It considers a magnetized collapsed star with a dipole magnetic field not aligned with its rotation axis. Rapid rotating plasma induce an electric field which extracts charges from the star's surface and these charges can escape from it following the open lines of force of the magnetic field. Particles moving away from the star reach relativistic speeds allowing synchrotron emission.

Magnetic tower It is then possible to find synchrotron emission associated with active galactic nuclei. The emission mechanism is still under debate as it is linked to one of the most critical subjects of physics: the black holes. Let us consider one of the most accredited models: the magnetic tower. First of all, we might wonder what a magnetized plasma does when it falls into a black hole.
If we consider the magnetic field perpendicular to the accretion disk we can imagine that, during the fall, the plasma will heat and compress itself, hence the magnetic field intensity increases. Furthermore, if the black hole is spinning, it will twist the magnetic lines of force making them thicker in the inner regions due to the differential rotation under which the plasma is subjected. This leads to the acceleration of the particles along the magnetic lines of force that eject the plasma from the galaxy's nucleus giving the relativistic outflows of charged particles known as jets.

Chapter 2

Emission and spectral features

THE MAIN CHARACTHERISTIC of synchrotron emission is its **polarization**: the electric field vector is perpendicular to the magnetic field which has generated the emission. The degree of intrinsic polarization for an electron power law energy spectrum (see eq. (1.6)) with an isotropic electron distribution is

$$\Pi_{intr} = \frac{\delta + 1}{\delta + \frac{7}{3}} \tag{2.1}$$

that, for a typical value of $\delta = 2.5$, gives $\sim 70\%$. This is of significant value; however, it has been obtained under the assumption of a uniform magnetic field. This theoretical degree of polarization is reduced in most of realistic cases, where *non uniform magnetic field* and *Faraday rotation* occur.

The first must be considered since regions with different magnetic fields will produce different oriented polarized radiation, that combined will give an average degree of polarization.

The second consists in the phase displacement introduced from a magnetized plasma on a polarized wave, giving a rotation angle over a distance L wavelength dependent

$$\Delta\phi = \lambda^2 \overbrace{\frac{2\pi e^3}{m_e^2 c^2} \int_L n_e H_{\|} \, dl}^{R.M.} \ . \tag{2.2}$$

The term under the bracket is called *rotation measure* and is related to the electronic density n_e and the magnetic field component $H_{\|}$ along the line of sight. In particular cases it can be useful for the estimation of $H_{\|}$ in the interstellar medium, like we will see next with pulsars, on Paragrapher 3.1.

We will now see what are the circumstances that lead to deviate the power law synchrotron spectrum to the theoretical spectrum shown in Figure 2.1.

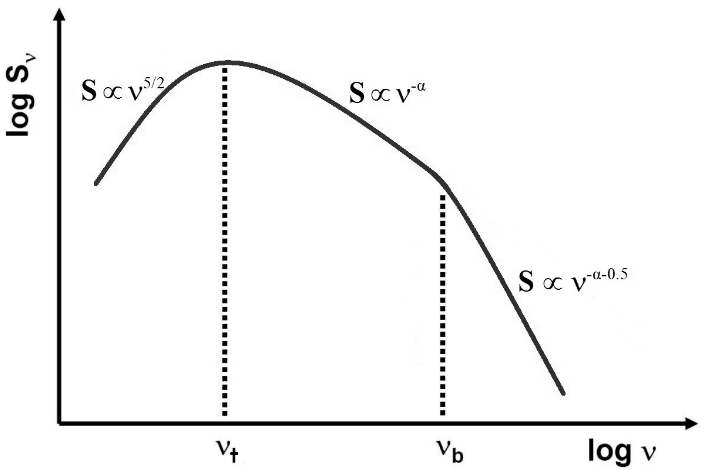

Figure 2.1: Theoretical synchrotron spectrum.

2.1 Time evolution of the spectrum

In an ensemble of particles, energy losses modify the spectrum of energy. The relative balance equation is

$$\overbrace{\frac{\partial N(\varepsilon,t)}{\partial t}}^{Particle\,flow} + \underbrace{\frac{\partial}{\partial \varepsilon}\left(\frac{d\varepsilon}{dt}N(\varepsilon,t)\right)}_{Energy\ losses} + \overbrace{\frac{N(\varepsilon,t)}{T_{conf}}}^{Leakage} = \underbrace{Q(\varepsilon,t)}_{Injection} \tag{2.3}$$

and it gives the behavior of the source with time. The left terms consider particles flux and the possibility that electrons could escape from the volume, the right term considers a possible injection of particles.

Particles energy losses due to synchrotron emission increase with time. Since particle life-time[1] is $t_b \propto (\varepsilon_0 H^2)^{-1}$, we conclude that those with higher energy (i.e. those producing higher frequency photons), are the ones that disappear earlier from the spectrum. This will modify it with a break for frequencies higher than the break frequency ν_b, which will shift to lower energies with time. The trends are

$$\begin{cases} J_s(\nu) \sim \nu^{-\alpha}, & \text{if} \quad \nu \ll \nu_b \\ J_s(\nu) \sim \nu^{-\alpha-0.5}, & \text{if} \quad \nu > \nu_b \end{cases} \tag{2.4}$$

and there is no change as far as low frequency photons are concerned.

The **steepening** of the spectrum then interprets the age of electrons population that has generate the emission.

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[1] It is the characteristic time for which electron energy is halved: $\varepsilon(t_b) = \frac{1}{2}\varepsilon_0$.

2.2 Self-absorption

New generated photons can be intercepted by ambient electrons. In this case, the radiative transfer equation provides a brightness

$$B_s(\nu) = \frac{J_s(\nu)}{4\pi\mu_s(\nu)}[1 - e^{-\tau_s(\nu)}] \tag{2.5}$$

where: $J_s(\nu)$ refers to synchrotron emissivity (see eq. (1.7)), $\tau_s(\nu)$ is the optical depht and

$$\mu_s(\nu) \simeq N_0 H^{\frac{\delta+2}{2}} \nu^{-\frac{\delta+4}{2}} \tag{2.6}$$

is the absorption coefficient for synchrotron radiation.

We can distinguish two different regimes

$$\begin{cases} B_s(\nu) \sim H^{-\frac{1}{2}}\nu^{\frac{5}{2}}, & \text{if} \quad \tau \gg 1 \\ B_s(\nu) \sim H^{\frac{\delta+1}{2}}\nu^{-\alpha}, & \text{if} \quad \tau \ll 1 \end{cases} \tag{2.7}$$

and notice that, in the case of optically thick regime, low frequency photons are highly absorbed which causes a low energy **turn over** in the spectrum.

We can then use the following equation

$$H \simeq \nu_t^5 \left(\frac{S_t}{\theta^2}\right)^{-2} (1+z)^{-1} \tag{2.8}$$

in order to estimate the magnetic field of the source, as it correlates directly measurable quantities: the turn over frequency ν_t and the flux density at that value S_t, the source's angular size θ and its redshift z.
However, we must undertake the following considerations:

– from eq. (2.6), we can see the dependence of the absorption coefficient by the density of the particles N_0. Therefore denser objects will be those with higher self absorption and, since brightness temperature is greater for small sources ($T_B \propto (\theta_1\theta_2)^{-1}$), we conclude that small objects are the ones more easily absorbed. This makes the estimation of the magnetic field more complex since its dependency from the angular size of the source; for that reason high resolution observations are required;

– expression (2.8) is true only in cases of **synchrotron self-absorption**: there may be other types of absorption and these would cause a more conspicuous turn over thus making the previous equation unusable.

2.2.1 Synchrotron self-Compton

Absorbed photons can contribute to the number of high energy photons. But, how can they increase their own energy?

Inverse Compton scattering consists of the energy transfer from energetic electrons to low energy photons. Since we saw that synchrotron radiation is generated from relativistic electrons, inverse Compton can occur in synchrotron self-absorbed sources; the process is then known as **synchrotron self-Compton**.

This phenomenon can provide an estimation of the source's magnetic field by the comparison between inverse Compton and synchrotron losses

$$\eta = \frac{\left(\frac{d\varepsilon}{dt}\right)_{ic}}{\left(\frac{d\varepsilon}{dt}\right)_{sync}} = \frac{u_{ph}}{u_{sync}} \tag{2.9}$$

where u_{ph} and u_{mag} are radiation and magnetic field densities respectively.

Outside the source, the main contribution to u_{ph} is given by the cosmic background radiation[2] but, within the source, it can be caused by the radiation produced by the object itself, then calculations must be done.

In case of $\eta > 1$ **Compton catastrophe** would occur: the main radiative process becomes inverse Compton and the source would be dominated by X-ray emission. However, low frequency photons are still observed; that problem is solved by interpretating the radio emission as a consequence of particles relativistic motion towards the observer and this povides the amplification of radiation.

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[2] Its energy density is now $\sim 0.26\, eV/cm^3$; however, this value is redshift dependent since it decreases with the universe age.

Chapter 3

Astrophysical examples

SYNCHROTRON RADIATION is typically a radio band phenomenon caused by previously low frequency photons generated, but for very high magnetic fields, the mechanism is extremely efficient and could provide even gamma-ray photons.

In order to see synchrotron emission in the astrophysical contex we must focus on objects with a magnetic field and a population of free electrons that are ready to accelerate. Approximate astronomy magnetic fields are shown in Table 3.1.

Table 3.1: Typical astrophysical magnetic fields.

	WD	NS	HII region	ISM	IGM	Radio Gl.	Gl. Cluster
H(G)	10^8	10^{12}	10^{-5}	10^{-6}	10^{-8}	10^{-6}	10^{-6}

The strenght of the fields rises up to several order of magnitude, from compact to very extended objects: we will have synchrotron emission on a exteneded range of scales.

In the next paragraphers, we will consider this radiation coming from four astrophysical objects: pulsars, supernova remnants, radio galaxies and galaxy clusters. The coiche of these objects is not casual; indeed we wanted to give as possible a generic description of the synchrotron radiation: we have two examples of *galactic* nature, pulsars and supernova remnants, and two concerning the *extragalactic* enviroment, radio galaxies and galaxy clusters. Furthermore, while pulsars and radio galaxies require ad hoc particle acceleration mechanisms, supernova remnants and radio halos in clusters use Fermi mechanism, that we will then see applied on very different size scales.

3.1 Pulsars

Firstly observed by Jocelyn Bell and Anthony Hewish in 1967, **pulsars** are one of the most amazing laboratories in the universe for their unique features.

At the end of stellar evolution, massive stars can produce compact objects (radii $\sim 10\,km$) made of degenerated neutrons (densities $\sim 10^{14}\,g/cm^3$). Pulsars are rapid rotating (periods can reach $\sim 10^{-3}\,s$) neutron stars, characterized by extremely high magnetic fields (strenght up to $\sim 10^{12}\,G$). Their typical mark is the radio pulse emitted[1], which gives them the name (PULsating rAdio souRces).

We have briefly argued pulsars emission mechanism proposed by T. Gold and F. Pacini. However, many details are not clear so far and considerable efforts are still going on to understand the emission under the extreme conditions that pulsars provide.

The radiation coming from pulsars shows typical synchrotron features. Spectral energy distributions of such objects are indeed domindated by a power law at radio frequencies; however, even very high energetic photons can be produced. For example, a polarized gamma-ray emission which is believed to have been caused by synchrotron mechanism has been detected in the famous *Crab pulsar* [Dean et al. 2008]. Many other pulsars provide high energy emission but not always the polarization, which is a distintive mark of synchrotron radiation, can be studied. Survey data with the *Fermi Gamma-ray Space Telescope* is giving a large contribute in such field and has already confirmed the existence of a radio-quiet class of pulsars.

Pulsars emission over a wide bandwidth is useful for probing the interstellar medium. In fact, when we observe such objects, pulses at different frequencies do not reach us at the same time because the dispertion of the medium in which the electromagnetic waves are travelling. Then we define the *dispersion measure* over a distance L

$$D.M. = \int_L n_e \, dl \tag{3.1}$$

that provide us, in case of signals delay, the electronic density n_e along the line of sight of the medium. Furthermore, if also the rotation measure (see eq. (2.2)) is available, an estimation of the average value of a magnetic field component can be done: $\langle H_{\|} \rangle \propto \frac{R.M.}{D.M.}$.

Therefore, pulsars are useful tools for mapping two important components of the interstellar medium.

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[1] This lighthouse effect is due to the star rotation: the object seems pulsating since we receive the radiation only when the magnetic pole points towards us.

3.2 Supernova remnants

We have seen that neutron stars are the left-over cores of high mass stars. Before such compact remnants are produced, one of the most violent phenomena in the universe occur: the star explosion.

In order to understand what happens, we must describe how the evolved internal structure of heavy stars appears. They are constituted by an onion-like structure made of envelops of star burned elements (from surface: H, He, C, O, Si) supported by an iron-core that cannot produce energy anymore.

When the center collapses, it becomes a neutron-core[2], which gives degeneracy pressure due to the Pauli exclusion principle. This will contrast the infalling material forcing the stellar gas outward and spreading it out into the interstellar space. Such an exploding star is called *supernova*[3].

In order to figure out where synchrotron radiation occurs in such a scenario, we must consider that during supernova events a large amount of energy is released in a very short time; only a few percent ($\sim 1\%$) goes to kinetic energy while the majority is released in the form of energetic neutrinos. The small fraction of kinetic energy is used to the acceleration of the stellar material which is ejected at supersonic speeds ($\sim 10^4\, km/s$). As the shock propagates, it will compress and heat the interstellar medium gas, forming a thin, dense shell: the **supernova remnant**.

The emission of these objects is detectable across a broad range of the electromagnetic spectrum.

We saw how shock waves are useful for the particles acceleration. Therefore, we will detect great radio emissions due to synchrotron mechanism.

Monthly radio observations from the supernova explosion allow the monotoring of the shell expansion and consequently the evolution of the synchrotron radiation: the almost istantaneous (and increasingly larger) radio emission proves the efficienty of Fermi mechanism associated with shocks.

X-ray emission is instead attributed to thermal bremsstrahlung as a consequence of the heating of the interstellar medium which can reach even $10^8\, K$. Shocks are also involved in such radiative process; however, in this case, their role consist in the ionization of matter providing free electrons to accelerate.

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[2] This is due to the electronic captures and the URCA processes that provide to remove degenerated electrons from the structure.

[3] This type of supernova is actually called a *type II supernova*.

3.3 Radio galaxies

Almost all massive galaxies host a central supermassive black hole which, in the 1% of cases, is active. *Active galactic nuclei* (AGN) provide an extremely strong emission, which is greater than the one that stellar radiation can supply. Such a huge source of energy is attributed to the infalling material in the central black hole, that is then cosidered as the power engine of AGNs.

In the past decades, many types of active galaxies were classified according to their observational properties. However, unified models suggest that the apparent differences between various AGNs is simply due to the angle of observation from the line of sight.

Radio galaxies are giant elliptical galaxies with optical properties similar to normal ellipticals and non-thermal nuclear activity mostly due to synchrotron radiation. They are very luminous at radio wavelengths but optical and X-ray radiation can also be detected. The strong emission made, and makes still now, AGNs very important in cosmology studies since they can be detected at high redshifts: the discovery of such distant sources has increased greately the size of the universe.

We briefly discussed the emission mechanism which involves a spinning black hole and an infalling plasma. However, this is only one simple scenario of the many models that have been done to explain the engine of AGNs.

While on one hand observations provided many useful informations for the knowledges of these objects, on the other, as already said, theoretical studies are in a deadlock due to the difficulty and unfamiliarity with the problem.

Nevertheless, radio galaxies present characteristic structures (see Fig. 3.1) which are identified as:

- The *core*: the compact central region, very difficult to resolve since its small dimension.
- The *jets*: highly collimated outflows of relativistic plasma originated in the central region of the AGN, can reach *kpc* or even *Mpc* scales.
- The *hot-spots*: the compact regions where the jets interact with the ambient medium. In them, the plasma is compressed and then the magnetic field amplificated.
- The *lobes*: extended sources lying in opposite directions, that may be separated by *Mpc* scales. They are constituted by the plasma ejected from the jets.

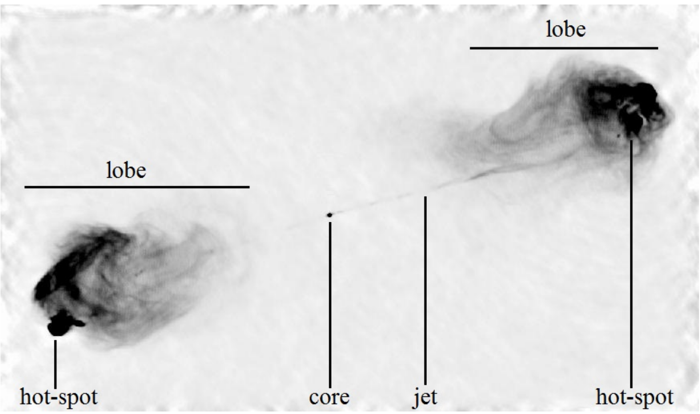

Figure 3.1: The radio source *Cygnus A* as an example of the typical morphology of radio galaxies [Perley et al. 1984].

Each structure is detectable in the radio band since its synchrotron emission which is enormously larger in respect of the optical dimensions of the galaxy hosting the AGN. Radio galaxies have an X-ray counterpart which is the result of inverse Compton and, again, synchrotron mechanism as far the jets are concerned, inverse Compton of the cosmic background radiation for the lobes and possibly by the synchrotron self-Compton process for the hot-spots.

Radio observations of such objects show that the steepening of the spectrum at low frequencies (see eq. (2.4)) is not a uncommon feature. Typical values of particles energy and magnetic field for a radio galaxy give $t_b \sim 10^8\, yr$; this suggests that a radio galaxy is a transient state of galaxy's life. Besides, statistical studies on the distribution of AGNs against the redshift demonstrated that the AGNs era has been around $z \sim 2$, when the universe was younger and there was more material which feeds black holes so much as to power AGNs.

3.4 Radio halos and relics

Cluster of galaxies are the most massive gravitationally bound systems in the universe and represent another unique laboratory at our disposal.

They may contain from hundreds to thousands galaxies within a space region size in the range 1-10 Mpc. Galaxies represent about 5% of the mass fraction of the clusters, that is dominated by the 80% of dark matter, the remaning 15% is constituted by the intergalactic plasma of the intracluster medium (ICM). This played an important role for the studies of these objects due to the informations obtained from its X-ray emission caused by thermal bremsstrahlung process.

Radio observations provided another large-scale emission in clusters due to synchrotron mechanism that demonstrate the presence of relativistic electrons and large scale magnetic fields in the ICM. But while X-ray emission is present in all clusters, widely diffused radio sources associated with the ICM are not a common features, so they must be generated under some specific conditions.

In the extragalactic enviroments, is not uncommon for it to occur in *galaxies mergers*. On a larger scale, we find analogous events that involve clusters and/or sub-clusters of galaxies. However, this does not represent anything cathastrophic; in fact, galaxies do not feel the effects of these collisions and they pass through almost without consequences. This is not true for the intergalactic gas which is involved in the collisions; that might produce shock waves and then acceleration of relativistic electrons may occur.

Diffused radio emissions are then extended in order of size of galaxy clusters. Depending on where the emission is located in the clusters, we distinguish three source types:

- **Radio halos** are extended ($\gtrsim 1\,Mpc$) sources located at the center of merging clusters. Their shapes are quite regular in morphology, which recall the X-ray emission. No polarization is detected down to a few percent.
- **Relics** are also detected in merging clusters and have similar extensions of radio halos. However, they are usually located at the cluster peripheries and show elongated shapes perpendicular to the cluster centers (therefore are considered as shock waves tracers). Besides, strong polarization ($\sim 10 - 30\%$) is detected.
- **Mini-halos** are smaller sources ($\lesssim 500\,kpc$) detected in cooling core clusters, then they differ from the previous two as they are not associated with any merger. Their emission surrounds the powerful dominant radio galaxy at the cluster centers.

The main relevant aspect of halos and relics is that they are not associated with any individual galaxy: merger events generate shocks in such great scales that Fermi mechanism is able to produce extended synchrotron sources that are the largest in the universe.

Conclusions

From the brief introduction to synchrotron radiation presented in the previous pages we realize that, in order to produce this emission, a high density of ultra-relativistic electrons and a magnetic field are both required. Many astrophysical objects satisfy these conditions and we have presented here some typical examples.

Astrophysical magnetic fields are typically weak, thus this kind of process is a low energy phenomenon. However, compact objects with extremely strong magnetic fields can generate even gamma-ray radiation.

The process extends over a wide range of scales starting from ultra-dense neutron stars within the galaxy, up to extended emission from galaxy clusters.

The physical process of synchrotron radiation is well known and raised only to address the problem as to how charged particles can be accelerated at relativistic speeds.

In the mid of the past century, many theories were advanced, some of which are still considered valid; amongst these Fermi mechanism remains prominent and, as we have seen, it sits well in the astrophysical contex. Furthermore, many models aimed at specific astronomical objects (e.g. pulsars) were born, which soon found confermation from the early radio astronomy.

Future prospects, thus, will focus on the astrophysical aspects of synchrotron phenomenon. Technical progress led to the building of large-sized radio interferometers, such as ALMA, LOFAR, the SKA percursors ASKAP and MeerKAT and finally SKA, there will make possible very high resolution observations at low frequencies, where synchrotron radiation is prevalent.

However, there is evidence almost everywhere that, in astronomy, there are correlations between observations at different energies and, for this reason, multi-frequency studies are required.

Useful information can also be gathered from numerical simulations and theoretical studies in different fields of physics; meaningful attention will then be focused on particles physics, accretion physics, MHD and plasma physics in general.

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