ALMA MATER STUDIORUM · UNIVERSITÀ DI BOLOGNA

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

MAIN CHARACTERISTICS OF THE EMISSION FROM ELLIPTICAL GALAXIES

Tesi di laurea in Astronomia

Relatore:
Prof. Daniele DALLACASA

Candidato:
Chiara D'EUGENIO

Sessione I
Anno Accademico 2013–2014

Sommario

Le galassie ellittiche rappresentano uno dei corpi celesti più caratteristici del cielo. Per svelarne le proprietà, come struttura e composizione chimica, occorre valutarne l'emissione nelle diverse zone dello spettro elettromagnetico. Esse sembrano comportarsi diversamente a seconda dell'occhio con cui le guardiamo. La loro luce infatti risulta legata a due componenti nettamente diverse: la radiazione ottica ha origine direttamente dalle stelle che compongono il corpo della galassia, mentre quella in X viene prodotta dall'alone di gas estremamente caldo che permea solitamente questi oggetti. Dopo una breve classificazione iniziale, verranno illustrati i due meccanismi principali in gioco, assieme alle informazioni che possiamo ricavare da essi. In ultimo, verranno accennati gli aspetti relativi alle restanti regioni dello spettro.

Abstract

Elliptical galaxies are one of the most characteristic objects we can find in the sky. In order to unveil their properties, such as their structure or chemical composition, one must study their spectral emission. In fact they seem to behave rather differently when observed with different eyes. This is because their light is mainly brought by two different components: optical radiation arises from its stars, while the X emission is primarly due to a halo of extremely hot gas in which ellipticals seem to be embedded. After a brief classification, the two main processes linked to these phenomena will be described, together with the informations we can collect thanks to them. Eventually, we will take a quick look at the other regions of the electromagnetic spectrum.

Indice

Introduction

Galaxies are the ultimate structures where stars are gathered. According to the *Hubble Sequence*, we can divide these objects into three main morphological classes: elliptical, spiral and irregular galaxies, with a transition element between the former two represented by lenticular galaxies (S0). The aim of this work is to describe the radiation coming from elliptical galaxies, its main features and how it is produced.

General Aspects

Ellipticals (E's) owe their name to their characteristic shape, which can range from a perfect circle to a quite flattened ellipsoid. Lacking almost completely of dust structures and cool gas, they are immune to the heavy estinction experienced by spiral galaxies. So, as they are fairly transparent objects, the stellar component represents the dominant emission feature of these systems, together with a halo of extremely hot gas detectable only in X-rays. E's appear as smooth objects: we have a high luminosity central region, the *core*, where light is produced by a dense and chaotic stellar environment; surrounded by a looser region which fades away with no detailed contour. In general, ellipticals are mainly composed of red giants and stars on the asymptotic giant branch, born at the same time in an early burst of star formation activity. We have then a very small fraction of hot, young blue stars; thus causing the visual emission to be redder than that of spirals. Only 5%−10% of normal ellipticals show some dust emission with structures such as lanes or shells, while atomic hydrogen (H I) or molecular gas is hardly detectable. On the other hand, E's typically contain a significant amount of hot gas produced by dying stars, usually from 10^9 to $10^{11} M_\odot$ for the brightest ones. This gas is too diffuse to emit or absorb in the radio and optical regions of the spectrum but it is so hot to thermally radiate in the X-rays. Therefore, since the mass contributions by cool gas and dust are generally negligible with respect to the total mass and since the hot gas appears to be prominent, we will focus our attention on the radiation coming from this last one. Lastly, observations of close ellipticals show that almost a 50% of them have highly ionized gas centered around the nuclear region, presumably due to an AGN accretion activity. Since a deep look at AGNs lie outside the first degree course, this kind of emission will not be examined.

Since emission profiles can vary according to the kind of elliptical galaxy, in the following section a list of the main types is reported.

Classification

We gain informations on the emission of a galaxy by measuring its *Surface Brightness*:

$$I(x) = \frac{L}{4\pi D^2} \qquad [mag\ arcsec^{-2}] \tag{1}$$

where L is the integrated stellar luminosity, D is the side of the area covered on the sky plane and x is a point of the analised image. Basically I(x) is the amount of light per square arcsecond we observe on the sky and it is independent from the distance between the source and the observer. When analising a galaxy image we can take contours of costant surface brightness, called *isophotes*, usually measured in the B band, which can provide a useful tool as it follows: initially E's were classified solely on their shapes, according to the apparent ellipticity of the object:

$$\epsilon = 1 - \frac{b}{a} \tag{2}$$

where a and b are the semi-major axis and the semi-minor axis of a chosen isophote respectively. The more their ratio is close to one, the rounder the galaxy appears. Usually E's are reported using the Hubble type En, where $n = 10\epsilon$, so that an E0 has a perfect circular shape while, for example, an E5 has an axis ratio of 0.5, meaning of course that a is twice the size of b. This kind of classification depends strictly on the viewing direction of the observer, since, as said before, ϵ refers to an apparent quantity, resulting from the projection of the galaxy image on the sky plane.
We can go further in dividing elliptical galaxies by taking account of their mass, size and absolute B magnitude:

- *cD galaxies* are extremely bright and massive systems. Their diameter can reach out to 1Mpc and are found only near the center of large and dense galaxy clusters. They have masses ranging from 10^{13} to $10^{14} M_\odot$ and absolute B magnitudes (M_B) between -22 mag and -25 mag;

- *Normal elliptical galaxies* also include giant ellipticals (gE's) and compact ellipticals (cE's). Their diameters can reach 200 kpc, with typical total masses on the order of $10^8 - 10^{13} M_\odot$. Their are characterised by $M_B = -15 \div -23$ mag;

- *Dwarf elliptical galaxies* (dE's) have smaller diameters: from 1 to 10 kpc. Their masses can vary between 10^7 and $10^9 M_\odot$ with $M_B = -13 \div -19$ mag. They represent the majority of galaxies in the Local Group. However, they are mostly observed in the vicinity of the Milky Way or in nearby galaxy clusters because of their low luminosities;

- *Dwarf spheroidal galaxies* (dSph's) show low surface brightnesses, $M_B \sim -15$ mag and low luminosities. The largest diameters for these objects can barely reach 1 kpc, while their masses can measure $10^7 - 10^8 M_\odot$. They can be divided into two subclasses: compact and diffuse according to whether they show a high or low central surface brightness.

In the following chapters we will analise the two main portions of the electromagnetic spectrum in which elliptical galaxies show a significant behaviour: first of all we will take a look on the visual band; then we will move to the high energy section, since ellipticals are strong X-rays sources.

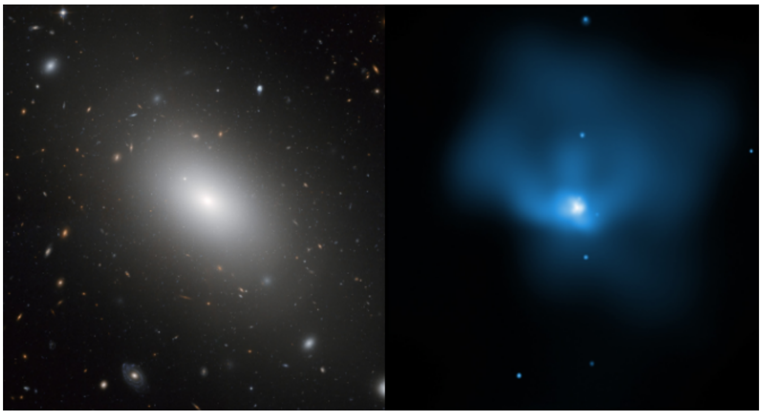

Figure 1: Optical and X-ray images of the elliptical galaxy NGC 1132 about 300 million light years away. Obtained by the *HST* and the *CHANDRA X-Ray Observatory*. Hubble's data reveal a giant foreground elliptical galaxy, plus numerous dwarf galaxies in its neighborhood, and many distant galaxies in the background.The blue/purple in the image is the X-ray glow from hot, diffuse gas detected by Chandra. *Image Credit: Optical: NASA/ESA/STScI/M. West; X-ray:NASA/CXC/Penn State/G. Garmire.*

Chapter 1

Optical emission

1.1 Main Relations

Visible light coming from ellipticals is well fitted by a characteristic empirical formula, known as *Sersic's law*:

$$I(R) = I_e exp\{-b[(R/R_e)^{1/n} - 1]\} \tag{1.1}$$

where the coefficient b is chosen so that half of the total light of the galaxy is confined within a circular area of effective radius R_e. Therefore, I_e is clearly I(R_e). Depending on the type of galaxy, this relation can be adjusted. In order to fit the observed surface brightness profile, we can vary the free parameters b and n. Normal and giant ellipticals tipically show profiles where $b = 7.67$ and $n = 4$. In this case we refer to eq.(1.1) as $R^{1/4}$ or *De Vaucouleur's law*(1948); its slope is clearly visibile in the first panel of fig.(1.1). We can also see that cD's show a deviation from this law at large radii - where the slope is less steep - probably due to the luminous halo of the environment in which they are often found. On the contrary, diffuse dE's appear to closely follow a simple exponential law:

$$I(R) = I_d exp\{-R/R_d\} \tag{1.2}$$

where R_d is called the *disk scale length* as this formula is often applied to describe galactic disks.

In elliptical galaxies, I(R) and L are linked to each other. Interestingly, the central surface brightness in cD systems decreases with increasing luminosity, while it increases for dimmer objects such as dE's and dSph's, for which $M_B \geq -18$ mag or $L \leq 3{\cdot}10^9 L_\odot$. The luminosity of an elliptical is also strictly linked to the motion of its stars. Note that stellar motion in these objects is quite random, in contrast with the neat pattern showed by spirals. Without getting into deep dynamical considerations, we can introduce the *Faber-Jackson* relation:

$$L \propto \sigma^4 \tag{1.3}$$

which connects an E's luminosity to the central velocity dispersion of its stars. Typically:

$$\left(\frac{L_V}{2 \cdot 10^{10} L_\odot}\right) \approx \left(\frac{\sigma}{200km\ s^{-1}}\right)^4 \tag{1.4}$$

measured in the V band. σ measures how much spread is the central stellar velocity distribution and it can range from roughly 50 km s^{-1} to 500 km s^{-1} according to whether one observes the faintest or the brightest systems respectively.

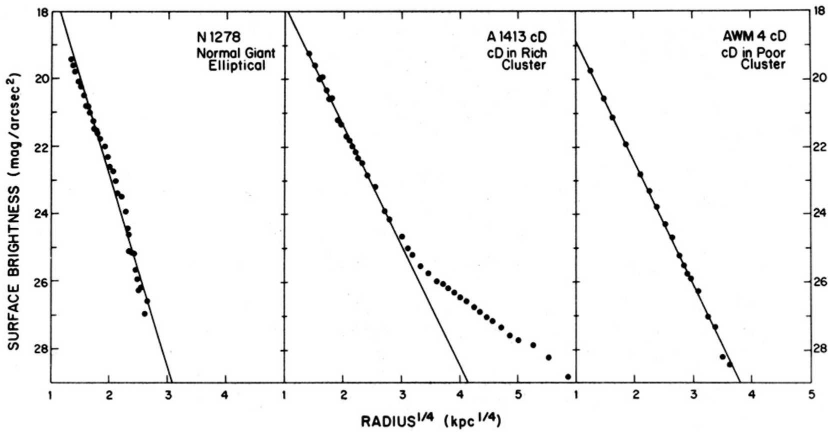

Figure 1.1: Radial surface brightness profiles for a gE and for cD's in two different environments.

There is a much more general correlation between all the observable parameters seen above: elliptical galaxies seem to lie rather closely to a plane in a three-dimensional space, on whose axes we have σ, the effective radius R_e and the surface brightness I_e. This surface is the *fundamental plane* and it is approximately given by:

$$R_e \propto \sigma^{1.24} I_e^{-0.82} \tag{1.5}$$

The previous relations turn out to be projections of the fundamental plane and have a higher intrinsic scatter.

1.2 Blackbody Radiation

As said in the previous section, the predominant source of light in the visual band for these objects comes from their stars. A star radiates approximately like a *black-*

body (BB), namely an ideal object at Thermal Equilibrium, capable of absorbing all the incoming radiation and irradiate the same amount of energy. According to the *Kirchhoff's law*(1860) this behaviour can be written as:

$$\epsilon(\lambda) = \alpha(\lambda) = 1 \tag{1.6}$$

where α is the spectral absorbance of a medium, defined as the ratio of the absorbed energy to the incident power at a given wavelength. ϵ is the emissivity of the same medium, i.e. its intrisic capability of emitting energy, usually referred to that of a blackbody, hence $\epsilon = 1$ here.
Now, a star is hardly an object at thermal equilibrium, in fact the temperature decreases steeply from the core to the photosphere. Fortunately we can always consider shells or layers small enough where a Local Thermodynamic Equilibrium is established: fluctuations in T within each layer can happen, but in such short time scales so that T can be considered costant. A costant temperature would imply that "no extra energy is stored", meaning that every layer irradiates all the incoming absorbed energy.

The *Spectral Brightness* of a BB is ruled by *Planck's radiation law*:

$$B(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \qquad [erg\ s^{-1}\ cm^{-2}\ Hz^{-1}\ sr^{-1}] \tag{1.7}$$

where $h = 6.62 \cdot 10^{-27} erg\ s$ and $k = 1.38 \cdot 10^{-16} erg\ K^{-1}$ are the *Planck* and *Boltzmann constants* respectively, T is the equilibrium temperature [K] and $c = 3 \cdot 10^{10} cm\ s^{-1}$ is the speed of light. As we see in fig.(1.2) each BB profile is strictly dependent on the value of T and there is no crossing whatsoever among the lines, meaning that a "warmer" BB will radiate more energy than a "cooler" one. Every curve is peaked on the frequency where the maximum amount of energy is released, the position of ν_{max} is related to the equilibrium temperature by the *Wien's displacement law*:

$$\nu_{max} = 5.88 \cdot 10^{10}\, T \qquad [Hz] \tag{1.8}$$

showing how cooler stars will have the maximum emission at lower frequencies, i.e. at longer wavelengths. It's clear that the typical BB curve follows two slopes according to the value of $h\nu/kT$ that is the ratio between the energy of the produced photon and the mean thermal energy of the BB. For high frequencies we see an exponential decay in the spectum, as described by the *Wien approximation*:

$$h\nu/kT \gg 1 \qquad B(\nu, T) = \frac{2h\nu^3}{c^2}\, e^{-\frac{h\nu}{kT}} \tag{1.9}$$

while at lower energies, the emission follows a distribution given by the *Rayleigh-Jeans approximation*:

$$h\nu/kT \ll 1 \qquad B(\nu, T) = \frac{2h\nu^3}{c^2}\,\frac{kT}{h\nu} = 2kT\,\left(\frac{\nu}{c}\right)^2 \tag{1.10}$$

If we integrate the spectral brightness over the frequency, we obtain the *Stefan-Boltzmann law*:

$$B(T) = \frac{\sigma_{SB}}{\pi} T^4 \qquad [erg\, s^{-1}\, cm^{-2}] \tag{1.11}$$

which shows us how the bolometric brightness of a blackbody depends only on its temperature. $\sigma_{SB} = 5.7 \cdot 10^{-5}\, erg\, s^{-1} cm^{-2} K^{-4}$ is of course the *Stefan-Boltzmann* costant.

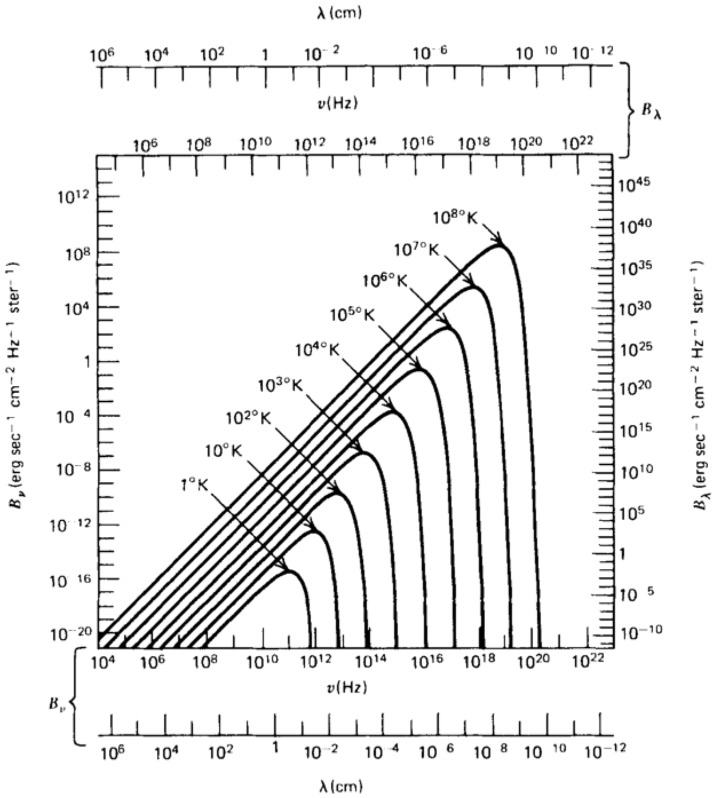

Figure 1.2: Log-log plot of blackbody spectra for various temperatures. Note the displacement of the peak for each curve given by eq.(1.8)

As said in the previous section, elliptical galaxies appear to be redder than spiral galaxies. An important point is to understand whether this feature is due to the galaxy age or to its chemical composition. In fact, this equals solving a degeneracy in E's appearence introduced by a similar optical behaviour for both an "old" galaxy, lacking the blue emission from newly born stars, and a fairly metal-rich environment produced by SNe over time. Since we cannot resolve individual stars in galaxies lying more than 20Mpc away, we have to rely on the integrated information provided by spectra. A typical spectrum of an elliptical galaxy shows strong absorption lines plus a strong break in the emission around 4000 Å produced by the metal-rich environment. Note that each of these lines is a sort of blending between all the absorption lines created by individual stars, as a result of the limited spectral resolution. Moreover, we can see a significant reduction in the emitted power for wavelengths shorter than 3500 Å, which is a sign of the absence of hot young stars, such as type O and B. These informations suggest that ellipticals are commonly made of population II stars with a wide range of metallicities resulting from an early stage of star formation, that quickly enriched the ISM of α-elements. These stars are generally low mass objects ($\leq 2M_{\odot}$), that have left the main sequence and are now red giants or stars on the asymptotic giant branch mainly emitting in the red band, similarly to those found in the bulges of spiral galaxies.

Interestingly the most luminous and massive ellipticals appear richer in metals, hence redder, than low-mass ones. In fact, as a result of their stronger gravitational potential they were more efficient at trapping heavy elements and incorporating them into new stars.

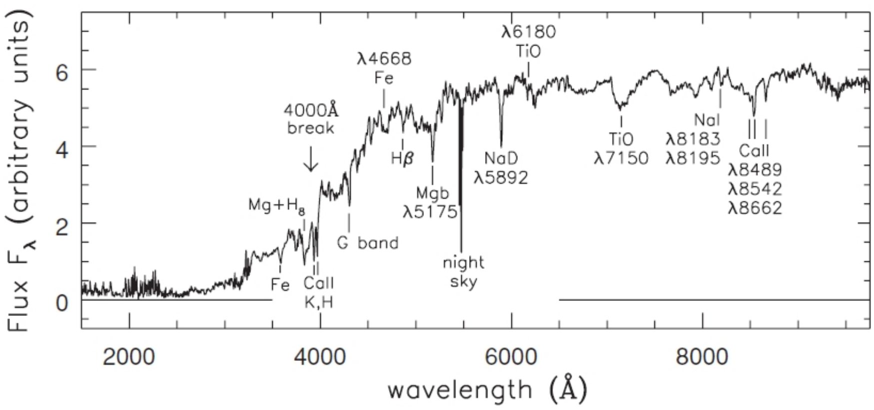

Figure 1.3: A spectrum by a typical elliptical galaxy where the spectral flux is plotted agains the wavelength. Note the absorption lines by some of the α-elements, Fe and the 4000 Åbreak

Chapter 2

X-ray emission

The most relevant source of highly energetic photons $(0.1 \div 10keV)$ lies in the enormous amount of hot interstellar gas. With characteristic temperatures higher than 10^7K we have ionized matter, gathered into huge clouds of diffuse plasma ($n(0) \sim 0.1cm^{-3}$ at the center of gE's). For the brightest ellipticals, these clouds can span for over 30 kpc from the galactic center. This gas is initially heated by shockwaves arising from red giants and supernovae. At these temperatures even the heavy components of the interstellar gas are ionized. Therefore, we have a plasma composed of positively charged nuclei and individual electrons, cooling down via *Bremsstrahlung* (the german word for Braking Radiation). Generally we can assume the gas to be in thermal equilibrium, thus obeying to the *Maxwell-Boltzmann velocity distribution.* Consequently, the relativistic aspects of this phenomenon will not be analised. This thermal radiation is related to free-free processes among charged particles, this means that the energetic transitions are not discrete anymore, thus producing a continuum spectrum ranging from radio waves to the X-rays.

2.1 Single Event

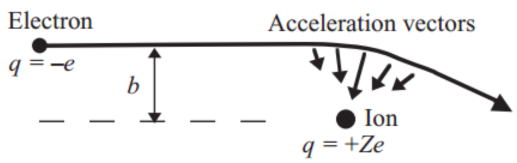

Figure 2.1: Schematic representation of a electron/ion collision

Let's consider the simple case where an electron moving with speed $\boldsymbol{v}$ encounters a stationary nucleus with charge Ze. The electron will get scattered by the electric field of the ion: it will be deflected from its original path undergoing a deceleration, i.e. an energy loss. In fact, the electron will radiate a certain power according to the *Larmor formula*:

$$P = -\frac{d\mathcal{E}}{dt} = \frac{2}{3}\frac{q^2}{c^3}\,a(t)^2 = \frac{2}{3}\frac{q^2}{m^2c^3}\left(\frac{d\boldsymbol{p}}{dt}\right)^2 \tag{2.1}$$

where $\mathcal{E} = \frac{3}{2}kT \approx \left\langle \frac{1}{2}mv^2 \right\rangle$ and $\boldsymbol{p} = m\boldsymbol{v}$ are the thermal energy and the momentum of the particle respectively. Therefore the emitted power is inversely proportional to the square mass of the decelerated particle. This implies that for an electron-ion interaction the emission arising from the ion will be negligible. In our case:

$$a = \frac{Z\,e^2}{m_e x^2} \tag{2.2}$$

where x is the distance between the two particles. This means that the power emitted becomes relevant only when the electron gets sufficiently close to the nucleus. If the electron loses only a small fraction of its energy its trajectory is slightly bent. We can therefore impose x to be the collision parameter b, that is the shorter distance from the nucleus reached by the electron if there were no interaction between the two. In this case the collision life span can be approximated to:

$$\Delta t \sim \frac{b}{v} \tag{2.3}$$

that is also the duration of the emission. This leads to:

$$P\Delta t \approx \frac{4}{3}\frac{Z^2 e^6}{m_e^2 c^3}\frac{1}{b^3 v} \tag{2.4}$$

This is the total energy radiated by a single electron passing by an ion in a hot plasma. As we can see: the shorter the collision parameter, the higher the emitted power. The radiated energy per frequency interval during each Δt is:

$$\frac{P\Delta t}{\Delta \nu} \approx \frac{16}{3}\frac{Z^2 e^6}{m_e^2 c^3}\frac{1}{b^2 v^2} \tag{2.5}$$

with a peak in:

$$\nu_{max} \approx \frac{v}{2\pi b} \tag{2.6}$$

2.2 Electrons in a Cloud

For a cloud of plasma where n_e and n_i are the electron and ion number densities respectively, the *total emissivity relative to a specific* $\boldsymbol{v}$ is the value resulting from eq.(2.5) times the number of collisions per second over all the possibile values of b. The number of collisions is given by the flux of electrons passing through an ion-centered annular region of radius b. We must then integrate this area over all the impact parameters which can range from a

$$(b_{min})_{quant} \geq \frac{\hbar}{m_e v} \tag{2.7}$$

to a

$$b_{max} \leq \frac{v}{\nu}. \tag{2.8}$$

where $\hbar = \frac{h}{2\pi} = 1.05 \cdot 10^{-27} erg\, s$ is the *reduced Planck costant*. After an integration over the velocity distribution, we eventually have the *total emissivity* J_{BR}:

$$J_{BR}(\nu, T) = 6.8 \cdot 10^{-38} n_e n_i Z^2 g_{ff}(\nu, T)\, T^{-1/2}\, e^{-\frac{h\nu}{kT}} \qquad [erg\, s^{-1}\, cm^{-3}\, Hz^{-1}] \tag{2.9}$$

g_{ff} is the *gaunt factor*, namely a correction due to quantum effects since some electrons can produce photons with $h\nu$ comparable to their own energy. These corrections depend on the ratio between b_{max} and b_{min} and are usually small (~ 1). As we can see, J_{BR} depends on the gas density and temperature but it is independent from ν except for the position of the break down. For this reason, it appears costant at low frequencies with an exponential decay (*cutoff*) for frequencies higher than $\nu_{cut} \approx kT/h$, since the electron can not radiate more than its own energy. By observing ν_{cut} we can then infer T.

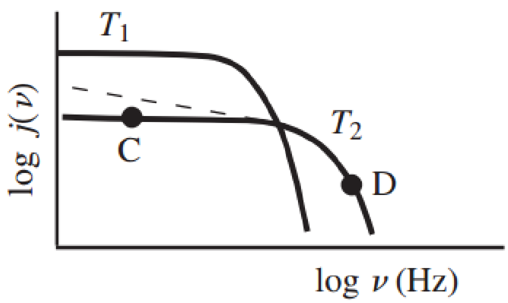

Figure 2.2: Log-log plot of the spectral emissivity for different temperatures, $T_2 > T_1$. Note that at low frequencies, a higher temperature means a lower emissivity.

Of course, a region radiating via Bremsstrahlung loses energy, hence it cools down. The *cooling time* is given by:

$$t_{BR} \sim \frac{6 \cdot 10^3}{n_e g_{ff}} T^{\frac{1}{2}} \quad years \tag{2.10}$$

meaning that the outer regions of an elliptical galaxy will cool down more slowly. From X-ray spectra we can gather informations on a galaxy composition. Generally the hot gas around elliptical galaxies is not hugely metal-rich with an abundance $\sim 0.5 Z_{\odot}$. Recent observations from satellites such as the *XMM Newton* show narrow emission lines produced by highly ionized metals in massive ellipticals, especially for those hosting an active central black hole.

A significant source of X-rays can also be found in X binaries. A few words will be spent for them as they go beyond the first degree course. These systems are often made of a massive star orbiting a white dwarf, a neutron star or a black hole. The accreting material falls on the latter component and releases its potential energy, thus emitting highly energetic photons.

Chapter 3

Other emissions:

3.1 UV

Despite their lack of young hot stars, metal-rich ellipticals are not completely dark in the UV band. The ultraviolet radiations may come from old metal-rich stars that have left the main sequence and, after losing most of their hydrogen envelope, leave the hot core exposed. No such stars are found near the Sun, since the Milky Way's disk is too young. So the models remain uncertain.

3.2 NIR

Near-Infrared radiation is generally weak for these objects, most of it comes from nearby ellipticals and it is due to the blackbody emission of individual sources, such as cool red giants. The observed surface brightnesses typically follow a De Vaucouleur's profile with some exceptions due to a small presence of cold ISM.

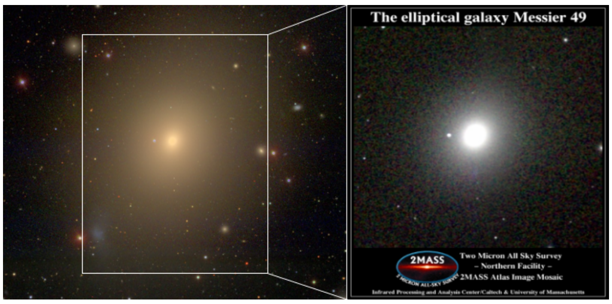

Figure 3.1: An optical image of the elliptical M49 (E2) compared with a $2\mu m$ image taken by the *2MASS. Image Credit: D. Hogg, M. Blanton and the SDSS Collaboration.*

3.3 Radio

Massive ellipticals are often associated with Synchrotron emission at radiowavelengths. This is a delicate subject as most of this radiation, together with significant UV and X-rays emission, is due to an accreting central black hole and therefore does not directly belong to the galaxy. When this occurs the elliptical is classified as “radio galaxy" and it is possibile to detect jets of highly relativistic particles ejected from the bright nuclear region. The two radio lobes can extend even ten times further from the galactic center than the optical component.

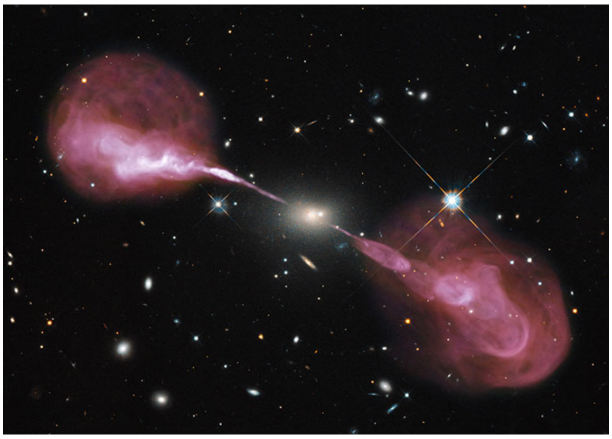

Figure 3.2: A composite image of the radio galaxy Hercules A. The white central region being the optical image of this giant elliptical.*Image Credit: NASA, ESA, S. Baum & C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team.*

Bibliography

[1] Sparke L. S., Gallagher J. S.,*Galaxies in the Universe: An Introduction*, Cambridge University Press (2007)

[2] Schneider P., *Extragalactic Astronomy and Cosmology: An Introduction*, Springer-Verlag (2006)

[3] Bradt H., *Astrophysics Processes: The physics of Astronomical Phenomena*, Cambridge University Press (2008)

[4] Binney J., Merrifield M.,*Galactic Astronomy*, Priceton University Press (1998)

[5] Carrol B., Ostlie D., *An Introduction to Modern Astrophysics Second Edition*, Pearson (2007)

[6] Ferrari A., *Stelle, galassie e universo. Fondamenti di Astrofisica*, Springer-Verlag Italia (2011)

[7] Rybicki G., Lightman A., *Radiative Processes in Astrophysics*, John Wiley & Sons, Inc. (2004)

[8] Dallacasa D., *Processi di Radiazione e MHD*, Dispense

[9] Cimatti A., *Formazione ed Evoluzione delle Galassie*, Slides

[10] Fanti C., Fanti R.,*Lezioni di Radioastronomia*, Dispense (1999-2000)

[11] Temi P., Brighenti F., Mathews W. G., The Astrophysical Journal 672,244 (2008)