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1 Introduction

All along the 20th century, many discoveries have revolutionised our current view of the Universe. The success of the special and general relativity predicted by Albert Einstein more than hundred years ago (Einstein 1905, 1916) is probably one of the most famous examples. A second major result is certainly the discovery of other ”island universes” by Edwin Hubble in 1926, extending our conception of the entire cosmos from the only Milky Way to a universe full of galaxies (Hubble 1926). Even more surprising is that, as also found by Hubble, these galaxies escape away from each other (Hubble 1929). This provided a solid piece of evidence that the Universe is actually expanding. A third major discovery, which quickly became a major issue for physicists and astronomers, was the evidence for missing (or ”dark”) matter, suggested independently in individual galaxies by Vera Rubin (1970) and in galaxy clusters by Jacobus Kapteyn (1922) and Fritz Zwicky (1933). Fourth, the accidental discovery of the cosmic microwave background by Arno Penzias and Robert Woodrow Wilson (1965; see also Dicke et al. 1965) provided a decisive proof of the Big Bang theory. Finally, the discovery of the acceleration of the expansion of the Universe by looking as distant Type Ia supernovae (Riess et al. 1998) suggests that the Universe is dominated by a mysterious ”dark” energy, whose fundamental nature remains unknown.

All these above discoveries are now fully part of the basic history of sciences, as they have had an extraordinary impact on the current way we conceive the Universe. Nevertheless, some past discoveries are somewhat less known to a large public, although they have not contributed less to fundamentally revisit our relation to astronomy. One of them deals with the question of the origin of the chemical elements.

1.1 The stellar nucleosynthesis: a brief history...

Only one hundred years ago, the origin of the chemical elements was still a total mystery for the scientific community. It had to wait until the progresses of quantum mechanics in the 1920's, before Sir Arthur Eddington (1920) and Jean Perrin (1922) proposed that the nuclear fusion of light elements like hydrogen could be a source of stellar energy. Later on, significant progress was achieved by Hans Bethe (1939) who set the first basis of the stellar nucleosynthesis theory by selecting two channels as the source of energy of stars:

1. The proton-proton chain reaction, believed to occur in low mass stars, where two protons eventually form a helium nucleus;

2. The CNO cycle, where carbon, nitrogen, and oxygen serve as catalysts to produce helium from protons in more massive stars.

At the time, however, stellar fusion theories did not explain how elements heavier than helium could form. Many years later, George Gamow (1946) proposed that these heavy elements, or "metals", had formed at the very first moments of the Universe. This was quantified more in the now well-known Alpher-Bethe-Gamow paper, published two years later (Alpher et al. 1948, which was found later to have correctly predicted the relative cosmic abundances of hydrogen and helium). On the contrary, Fred Hoyle suggested that metals are forged in the core of collapsing stars, after their hydrogen burning phase (Hoyle 1946). Finally, in 1952, Paul Willard Merrill detected absorption lines of technetium ($Z = 43$) in the spectra of R Andromedae and in other red variable stars. Since all the isotopes of technetium are unstable and thus short-lived, the natural conclusion was that significant amounts of this heavy element have been produced within the studied stars. While all the pieces slowly started to fit together with considerable progress from theories and observations, a complete and unified nucleosynthesis theory was still lacking.

The year 1957 has been decisive for the question of the origin of the elements. Almost simultaneously, two publications definitely gave birth to the modern stellar nucleosynthesis theory (Cameron 1957a; Burbidge et al. 1957). In particular, the second one — commonly named B^{2}FH following the authors (Margaret Burbidge, her husband Geoffrey Burbidge, William Fowler, and Fred Hoyle) — explicitly detailed all the processes responsible for the synthesis of all the heavy elements, from lithium to uranium. Two spectacular conclusions could be drawn from that paper.

1. It was definitely demonstrated that metals are synthesised in the cores of stars and, especially, in supernovae. On the contrary, the primordial nucleosynthesis is capable of creating hydrogen and helium only (as well as traces of lithium and berilium).

2. Perhaps even more importantly, the authors showed for the first time that when a star explodes as a supernova, it enriches its surrounding interstellar medium with its freshly created metals, thus participating actively in the formation of a new generation of stars.

In summary, about sixty years ago, evidence was provided that interstellar dust, planets, the Earth, living and human beings are all made of stars and supernovae, thereby revolutionising even further our conception of the Universe.

1.2 The role of Type Ia and core-collapse supernovae

Since 1957, stellar and supernova nucleosynthesis theories considerably improved (for an evolution of reviews, see e.g. Arnett 1973; Tinsley 1980; Arnett 1995; Nomoto et al. 2013). With the increase of computing performance (in synergy with the increasing number and quality of supernovae observations) from the end of the 1970's, several research groups started to simulate explosive nucleosynthesis in massive stars and supernovae while taking observational features into account (e.g. Arnett 1977; Weaver et al. 1978; Weaver & Woosley 1980; Nomoto et al. 1984).

Nowadays, it is well established that the production of metals can be distinguished as follows.

- Asymptotic giant branch stars synthesise carbon (C), nitrogen (N), as well as traces of neon (Ne) and magnesium (Mg) — e.g. Karakas (2010).

- Core-collapse supernovae (SNcc; Fig. 1.1 left panel) and their massive star progenitors synthesise almost all the oxygen (O), Ne, and Mg of the Universe, as well as a non-negligible fraction (about one half) of silicon (Si) and sulfur (S) — e.g. Kobayashi et al. (2006).

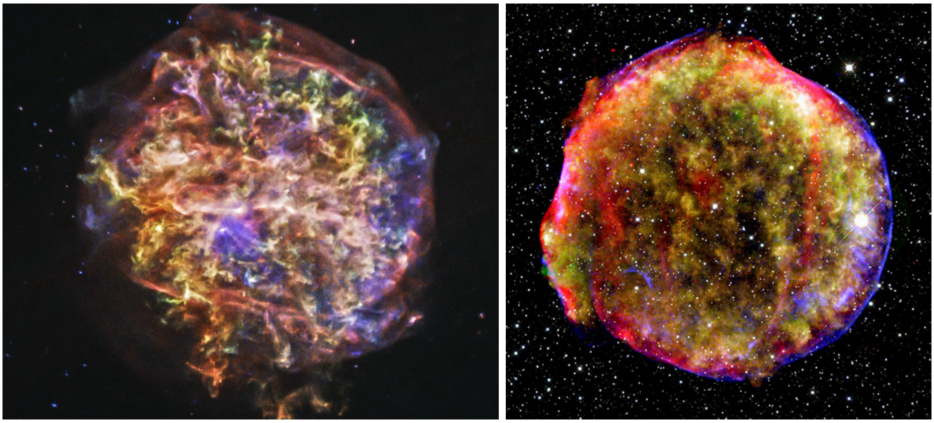

Figure 1.1: *Left:* Composite X-ray image of the (core-collapse) supernova remnant G292.0+1.8. Oxygen-dominated ejecta are shown in yellow and orange, magnesium-dominated ejecta are shown in green, and silicon and sulfur-dominated ejecta are shown in blue (Credit: NASA/CXC/SAO). *Right:* Composite image (red: mid-infrared; green and yellow: ejecta seen in X-ray; blue: shock front seen in X-ray; white: optical) of the (Type Ia) Tycho supernova remnant (Credit: X-ray: NASA/CXC/SAO, Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O.Krause et al.).

- Type Ia supernovae (SNIa; Fig. 1.1 right panel) synthesise the major part of argon (Ar), calcium (Ca), as well as the Fe-peak elements, in particular chromium (Cr), manganese (Mn), iron (Fe), and nickel (Ni) — e.g. Iwamoto et al. (1999). Moreover, as for SNcc, about one half of Si and S is produced in SNIa explosions.

- Heavier elements are thought to be synthesised via the r- and s-processes, plausibly in peculiar events like neutron star mergers (e.g. Martin et al. 2015) or during compact stellar binary assembly (e.g. Ramirez-Ruiz et al. 2015).

Throughout this thesis, we focus on the chemical elements produced by SNIa and SNcc (see Sect. 1.5). In the next subsections, we detail further the nucleosynthesis predicted for these two classes of objects, as well as the parameters and uncertainties that may affect it.

1.2.1 Core-collapse supernovae (SNcc)

When a massive star ($\gtrsim$8–10 $M_{\odot}$) has burned about 10% of its hydrogen into helium, it reaches the end of its life on the main sequence (typically within a few million years). Heavier elements (C, Ne, O, Si) are successively created, then burn in turn, building an onion-like structure in the core of the star, where heavier elements are synthesised in deeper layers. This burning process stops at ^{56}Ni (which further decays into stable ^{56}Fe), because nuclear fusion becomes energetically inefficient for higher isotopes. Consequently, Fe accumulates in the core and increases its density up to the electron degeneracy. When the core density reaches the Chandrasekhar limit ($\sim$1.4 $M_{\odot}$), the electron degenerate pressure is not sufficient anymore to counter gravitational contraction, and the core quickly collapses. Neutrons and neutrinos are then massively created by electron capture. This collapse suddenly stops when the core reaches the neutron degeneracy pressure, producing a powerful reverse shock from the core toward the upper layers. As the shock traverses the less dense external layers, its velocity increases and can reach about 25% to 50% of the speed of light, heating the upper stellar material (which rapidly synthesises more elements) and violently ejecting it into the interstellar medium. A core-collapse supernova is born. For recent reviews on the mechanisms driving SNcc explosions, see e.g. Janka (2012); Burrows (2013).

SNcc are commonly associated to Type II supernovae (i.e. supernovae showing hydrogen in their spectrum), but also to Type Ib (if the star has lost its hydrogen layer) and Type Ic supernovae (if the star has lost its hydrogen and helium layers). As mentioned above, their main nucleosynthesis products are O, Ne, and Mg which are created almost exclusively in SNcc, as well as Si and S whose production originates from both SNcc and SNIa (see also Sect. 1.2.2). Heavier elements like Ca, Ar, Fe, and Ni may also be synthesised during SNcc explosions, but at much lower quantities.

How much mass of these elements are created by a SNcc or, in other words, what are the typical yields that a single SNcc produces? According to the current SNcc models, the answer to this question depends on two main parameters:

1. The mass of the stellar progenitor;

2. The initial metallicity of the progenitor or, in other words: was the progenitor previously enriched by past supernovae?.

Of course, instead of considering only one SNcc, one can also address the same question for a collection of SNcc resulting from a same single stellar population. In this case, one must integrate the above parameters over the whole stellar population. Generally speaking, the integrated yields of a population of SNcc will depend on the initial mass function (IMF) of the progenitor population, and on its average initial metallicity, supposed to be very similar for all the population members (Fig. 1.2 top).

1.2.2 Type Ia supernova (SNIa)

Type Ia supernovae are different from SNcc in many aspects. In particular, they are not the result of the end-of-life of a massive star. Instead, is it generally admitted that SNIa progenitors are binary systems including at least one carbon-oxygen white dwarf, i.e. the stellar remnant of a low-mass ($\lesssim 8$ $M_{\odot}$) star, which suddenly gets (re-) ignited by mass accretion from the companion object. Unlike sometimes claimed, and because they do not result from a gravitational collapse, SNIa or their progenitors approach the Chandrasekhar limit, but never reach it. Although the precise mechanism is still unknown, the ignition is thought to be triggered by the explosive burning of carbon and newly synthesised nuclei. Because the electron degeneracy is independent of temperature, the white dwarf is unable to regulate its thermonuclear fusion, e.g. by expanding and cooling down, as a main sequence star supported by thermal pressure would naturally do. This somehow triggers one or several ignition flames, resulting in a violent explosion entirely disrupting the object (contrary to SNcc, where the remaining stellar core collapses into either a neutron star or a black hole), and ejecting its material into the interstellar medium. For reviews on the mechanisms driving SNIa explosions, see e.g. Hillebrandt & Niemeyer (2000); Hillebrandt et al. (2013). Within a couple of seconds, many heavy elements are created from the multiple explosive burnings. In particular, SNIa are thought to synthesise most of the Ar, Ca, Cr, Mn, Fe, and Ni, and about half of the Si and S present in the Universe. On the contrary, because lighter metals like C, O, Ne, and Mg are actually the fuel that is being burned during the explosion, not many of these elements remain after the explosion.

Although SNIa are widely used as standard candles to measure cosmological distances (and provide thus crucial help to estimate the acceleration of the expansion of the Universe, e.g. Riess et al. 1998), they are poorly understood astrophysical objects.

First, the physics of the explosion, or more precisely the precise propagation of the burning flame, is poorly known. Among the supernova community, two (or three) models are currently competing:

- The deflagration model, in which the flame is assumed to propagate subsonically through the exploding white dwarf;
- The delayed-detonation model, in which below a certain critical density, the flame becomes supersonic before reaching the surface;
- A third model, the pure detonation, in which the flame propagates always supersonically, is less plausible, though sometimes evoked.

In parallel to the mass and initial metallicity of the SNcc progenitors (Sect. 1.2.1), it is important to note that the nucleosynthesis yields of SNIa are very sensitive to the explosion model considered. In particular, deflagration explosions should produce significantly more Ni and less Si, S, Ar, Ca, and Cr with respect to delayed-detonation explosions (Fig. 1.2 bottom). This means that an accurate measure of SNIa yields may help to favour specific models, and thus better constrain the explosion mechanism.

Second, and perhaps even more embarrassingly, the precise nature of the progenitor companion is still unclear. The reason is that the observed variation in properties of SNIa is not well understood. In practice, it appears to be difficult to derive the nature of the progenitor from the SNIa lightcurve and spectrum (for recent reviews, see Howell 2011; Maoz & Mannucci 2012; Maoz et al. 2014). Currently, the two main progenitor channels proposed are:

- The single-degenerate channel, in which the companion is a non-degenerate star. Its material is progressively accreted by the white dwarf via Roche lobe overflow until carbon ignition of the latter;
- The double-degenerate channel, in which the companion is an other white dwarf. The ignition can then be triggered either by a violent merger, or by slow accretion if one white dwarf gets disrupted before reaching the other.

Whereas many observational constraints may be useful to favour/disfavour one particular channel, each of these two scenarios has its strengths and weaknesses, and the situation is still far from being clear. Among these constraints, a promising one is the determination of the delay time distribution, i.e. when do SNIa explode after the formation of an initial single stellar population. While it is clear that the delay time between a star birth and a supernova is longer for SNIa than for SNcc since (i) low-mass stars live longer and (ii) there may be substantial time between the white dwarf phase and the SNIa explosion within the binary system, its distribution for SNIa is still poorly constrained, yet very dependent on the dominant channel.

Unfortunately, a precise link between the progenitor scenarios and the explosion channels is still somewhat unclear. Indeed, each progenitor scenario allows both deflagration and delayed-detonation explosions (sometimes also called near-Chandrasekhar explosions; e.g. Nomoto et al. 2013). However, and interestingly, the scenario of a violent merger between two white dwarfs should in principle produce a sub-Chandrasekhar explosion, namely a pure detonation (Seitenzahl et al. 2013a). In principle, this specific scenario can thus be tested via an accurate measure of the SNIa yields.

1.3 Metals in clusters of galaxies

Because SNIa and SNcc eject freshly processed metals into their surroundings, it is not surprising to detect these elements within galaxies, whether in the form of interstellar gas or dust grains, thereby forming planets and even life. However, metals also enrich the circumgalactic medium, where their presence is confirmed even at high redshifts via their metal lines absorbing the light of background quasars ($2 \gtrsim z \gtrsim 5$; for a review, see McQuinn 2016). Even more surprisingly, metal enrichment is also found well beyond this (circum-) galactic limit; that is to say, the scale of clusters of galaxies.

Galaxy clusters are in fact the largest gravitationally bound structures known in our Universe. Since the Big Bang (about 13.7 billion years ago), they have assembled from local gas and dark matter over-densities, and grow continuously in hierarchical structures via mergers. The major component ($\sim$85% in mass) of galaxy clusters is in the form of dark matter, whose precise nature is still unknown. Stars, planets, interstellar gas, and galaxies constitute only about $\sim$10–20% of the remaining baryonic content. The other $\sim$80–90% of the baryonic mass is found in the form of a very hot (10^7–10^8 K), extended, highly ionised, and tenuous (10^2–10^4 atoms/m^3) gas, which fills the very large gravitational potential well of the whole cluster. This plasma, namely the intra-cluster medium (ICM, Fig. 1.3) is hot enough to emit X-ray radiation, essentially via bremsstrahlung ("free-free"

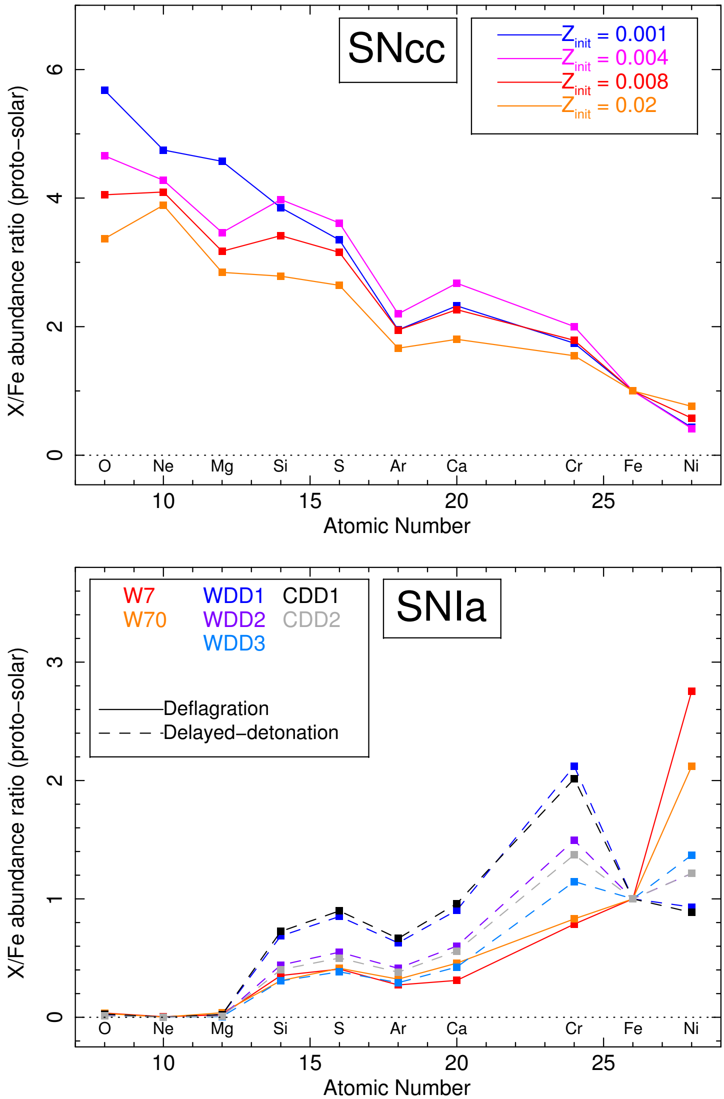

Figure 1.2: Predicted X/Fe abundance ratios from various SNcc (*top*) and SNIa (*bottom*) yield models. The SNcc yield models are adapted from Nomoto et al. (2013) and integrated over a Salpeter IMF between 10 $M_\odot$ and 40 $M_\odot$, and are shown for different assumed progenitor initial metallicities (Z_{init}). The SNIa yield models are directly adapted from Iwamoto et al. (1999). The W7 and W70 models reproduce a pure deflagration explosion while the other models (WDD1, WDD2, WDD3, CDD1, and CDD2) reproduce a delayed-detonation explosion. More details on all these models (and others) are provided in Chapter 4.

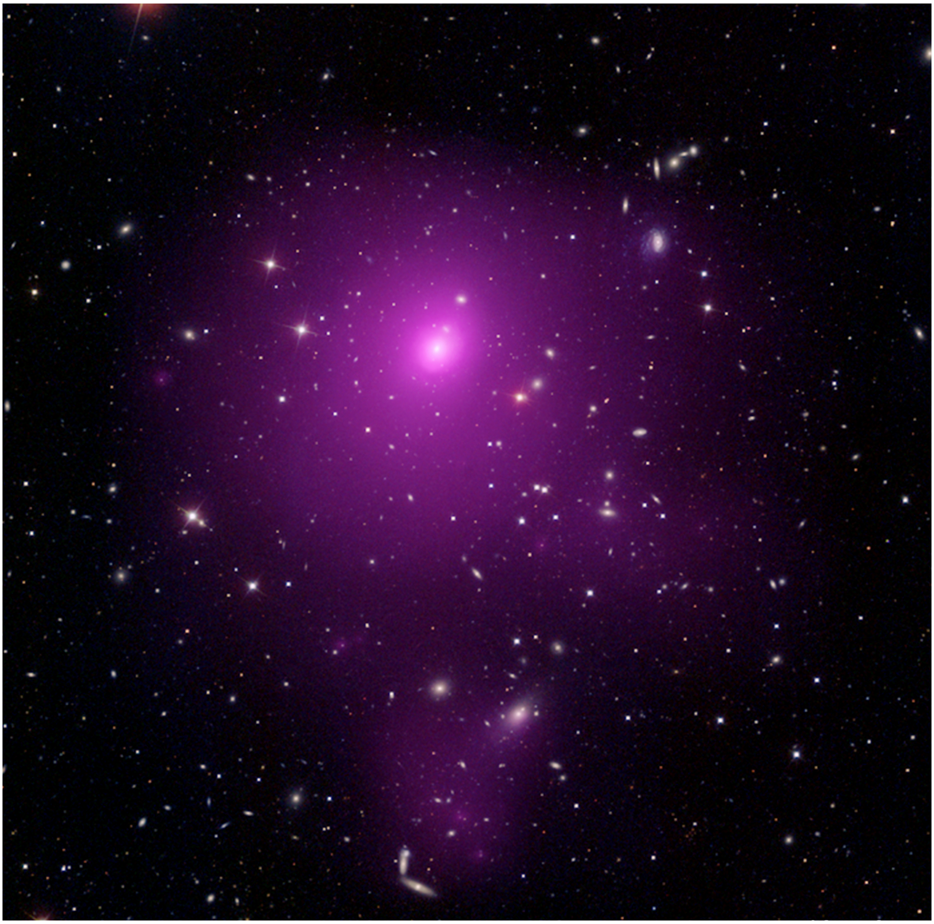

Figure 1.3: Composite image (purple: X-ray; white: optical) of the rich galaxy cluster Abell 85 (Credit: X-ray: NASA/CXC/SAO/A.Vikhlinin et al.; Optical: SDSS). The southern subcluster is thought to fall into the main cluster.

radiation), radiative recombination (”free-bound” radiation), and emission lines (”bound-bound” radiation).

1.3.1 The legacy of past X-ray missions

Luckily, the thermal emission of the ICM falls remarkably in the energy window accessible by the past and current X-ray telescopes (~0.3–10 keV). When discovered by the first X-ray detectors aboard balloons and rockets (Byram et al. 1966; Bradt et al. 1967), and eventually by the first X-ray satellite *Uhuru* (Cavaliere et al. 1971; Kellogg et al. 1972, 1973), whether this extended emission originated from thermal (e.g. bremsstrahlung) or non-thermal (e.g. inverse-Compton) processes was still unclear. A breakthrough came in the late 1970's, with the Ariel V and OSO-8 X-ray missions, whose improved spectral resolution allowed to detect for the first time an Fe-K emission feature around $\sim$7 keV in the spectra of the Perseus, Virgo, and Coma clusters (Mitchell et al. 1976; Serlemitsos et al. 1977). This result was spectacular in two aspects: (i) it definitely confirmed the predominant thermal, collisional nature of the ICM; and (ii) it showed for the first time that the ICM is polluted by metals, providing evidence that chemical enrichment plays a role even at the largest scales of the Universe.

Since these pioneering studies, and all along the succession of several generations of X-ray observatories with improved technology and instruments, measurements of metals in the ICM (and their interpretation) considerably improved. Launched in 1978, the *Einstein* observatory allowed to detect line emission from other elements than Fe (Canizares et al. 1979; Mushotzky et al. 1981). Another valuable discovery made by the *Einstein* mission was that about half of the observed clusters show a sharp peak in the X-ray surface brightness. Converting this brightness into gas density[1] and estimating their gas temperature, it was found that the cooling time[2] at the centre of these clusters is shorter than the Hubble time ($\sim$ 14 Gyr) (Jones & Forman 1984; Stewart et al. 1984). In fact, these "cool-core" clusters (Molendi & Pizzolato 2001) are dynamically relaxed and usually exhibit a strong inverted temperature gradient in their cores. On the other hand, "non-cool-core" clusters show a more extended and disturbed X-ray surface brightness, and do not reveal a clear central ICM temperature drop.

A great step forward in chemical abundance studies of clusters occurred with the launch of *ASCA* in 1993. This Japanese mission provided for the first time a reasonable estimate of the abundances of O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni in the ICM (e.g. Mushotzky et al. 1996; Baumgartner et al. 2005). Furthermore, *ASCA* also allowed to study for the first time the spatial distribution of Fe within the ICM, and showed a clear increase in the abundance of this element toward the centre of the Centaurus clus-

[1]The X-ray surface brightness of the ICM is proportional to the square of the gas density.

[2]In the case of an isobaric radiative cooling of a gas of density n_e and temperature T, the cooling time, t_{cool}, is calculated as $t_{\mathrm{cool}} = 8.5 \times 10^{10}$ yr $\left(\frac{n_e}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T}{10^8\ \mathrm{K}}\right)^{1/2}$ (Sarazin 1986).

ter (Allen & Fabian 1994; Fukazawa et al. 1994). Later on, the Italian-Dutch mission *BeppoSAX* (launched in 1996) established a clearer picture of the Fe distribution in clusters. In particular, De Grandi & Molendi (2001) showed that, while cool-core clusters host an excess of Fe in their core compared to the outskirts, non-cool-core clusters have a systematically flatter Fe radial profile.

1.3.2 The recent generation of X-ray missions

Among the recent generation of X-ray observatories, three missions should be mentioned: *Chandra* (launched on 23 July 1999, still active), *XMM-Newton* (launched on 10 December 1999, still active; see Fig. 1.4), and *Suzaku* (launched on 10 July 2005, ended on 2 September 2015). Each mission has its own benefits and is optimised for different purposes.

Chandra has a remarkable spatial resolution and is optimised to study in detail ICM substructures such as cavities and buoyant bubbles in cool-core clusters, probably created by the activity of the powerful active galactic nucleus in the central brightest cluster galaxy (BCG).

The European Photon Imaging Camera (EPIC) and Reflection Grating Spectrometer (RGS) instruments onboard *XMM-Newton*, on the other hand, have a larger effective area coupled to a better spectral resolution, which makes this mission the best suited one to measure abundances in the core of galaxy clusters and groups. The high resolution of RGS, covering and resolving the O-K, Ne-K, Mg-K and Fe-L lines, is particularly interesting for the study of systems showing a sharp peak in their X-ray surface brightness (Fig. 1.5 top). However, the RGS instruments are slitless, meaning that the emission lines in obtained spectra are broadened because of the spatial extent of the sources. The EPIC instruments (namely MOS 1, MOS 2, and pn) have a poorer spectral resolution but a more extended spectral window, accessing the Si-K, S-K, Ar-K, Ca-K, Fe-K and Ni-K lines, thereby allowing to study the spectrum of any extracted spatial region (Fig. 1.5 bottom). In this thesis, we use the *XMM-Newton* instruments to derive abundances in the ICM (see Sect. 1.5).

Finally, and despite its rather poor spatial resolution, the big advantage of *Suzaku* resides in its low instrumental background, allowing to probe regions of fainter emission, such as cluster outskirts. As explained in the next subsections, complementary studies performed by these three missions have completed the current picture we have about chemical enrichment of the ICM so far.

Figure 1.4: Artist impression of the *XMM-Newton* satellite in orbit around the Earth (Credit: ESA).

The new generation of X-ray missions includes *Hitomi* (launched in February 2016), *XARM* (expected launch in 2021), and *Athena* (expected launch in 2028). These three missions were/will be equipped with microcalorimeter instruments, which allows a considerable improvement of the spectral resolution achieved so far. The expected contribution of this upcoming generation of satellites to cluster enrichment studies is discussed in detail in Chapter 7.

1.3.3 Constraining supernovae models by looking at the intracluster medium

As explained in Sect. 1.2, the yields that SNIa and SNcc release into their surroundings highly depend on several intrinsic physical assumptions such as the IMF and the average initial metallicity of the progenitor SNcc population, or the dominant explosion channel driving SNIa explosions. In principle, deriving the abundances in supernova remnants via their X-ray spectra would therefore help to constrain these assumptions and better understand the physics of supernovae and of their progenitors. In practice, however, this is very difficult for at least three good reasons:

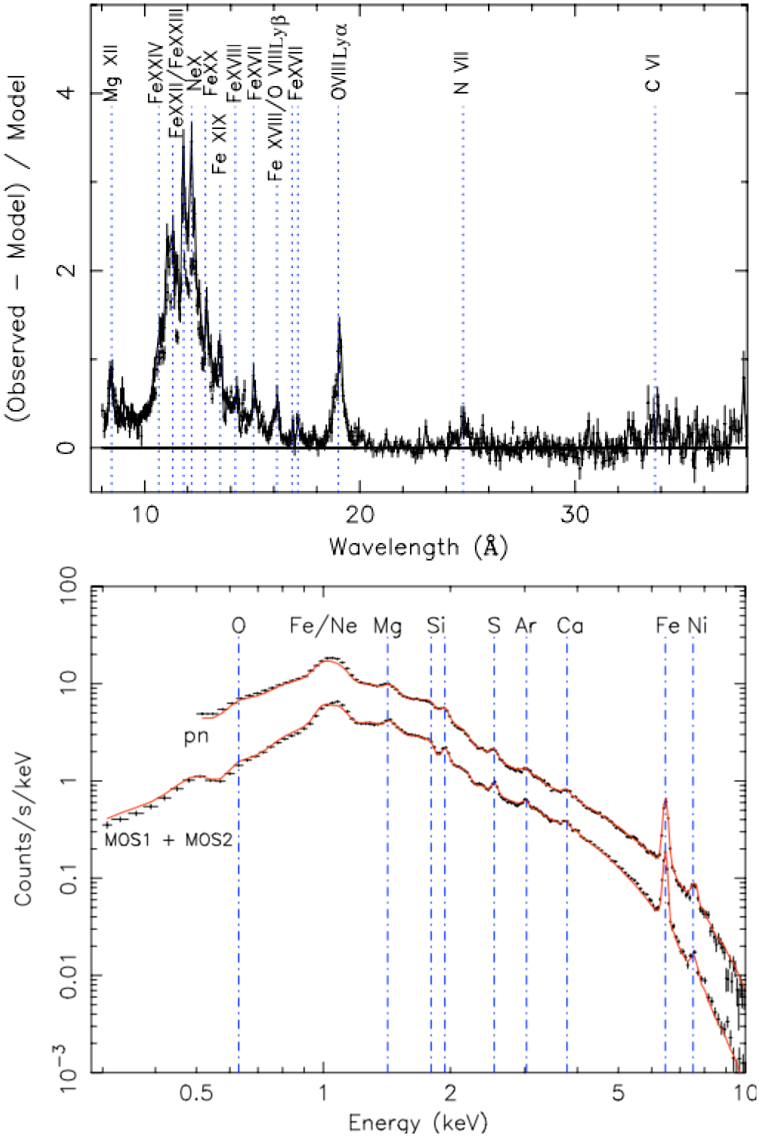

Figure 1.5: *Top: XMM-Newton* first-order RGS spectrum residuals of the core of the giant elliptical galaxy M 87, where line emission has been set to zero in the model (Werner et al. 2006a). *Bottom: XMM-Newton* EPIC (including MOS 1 + MOS 2 and pn) spectra of the core of the cluster 2A 0335+096, together with their respective best-fit spectral models (Werner et al. 2006b). The metal emission lines from which the abundances can be measured are indicated by the blue dotted (RGS) and dash-dotted (EPIC) lines.

1. Only a few tens of supernova remnants can be studied in our Galaxy or in its very local neighbourhood, preventing a comprehensive study on large statistical samples;

2. The ionisation state and the thermal structure of the hot plasma in supernova remnants are often complicated, which makes difficult the conversion of relative spectral line emissivities into chemical abundances;

3. The yields produced by the supernova ejecta may easily mix with the metals that were already present in the surrounding interstellar medium, thus complicating even more the direct interpretation of the measurements.

Because all heavy elements in the Universe have been produced in stars and supernovae, metals present in the ICM are nothing else as than the integral yields of billions of SNIa and SNcc having continuously enriched galaxy clusters during and prior their evolution. In fact, clusters act as ”closed-box” systems, as they are able to retain all the stellar products in their very large gravitational potential well. This implies that all supernovae exploding within the cluster remain locked either in their galactic hosts in the form of new stars or interstellar gas, or in the intra-cluster medium[3] (see also Sect. 1.3.5). Moreover, and contrary to supernova remnants, the ICM is optically thin and in collisional ionisation equilibrium (CIE). This means that abundances can be robustly measured in the ICM, as they are directly proportional to the equivalent width[4] of their X-ray emission lines. Consequently, the ICM provides a unique opportunity to constrain SNIa and SNcc models and to estimate the ratio of the number of SNIa/SNcc contributing by measuring the abundances of the elements they release in galaxy clusters and groups.

The pioneering study on this concept was done by Mushotzky et al. (1996) using ASCA observations. The authors concluded that their measured abundances in the ICM are consistent with a dominant SNcc contribution to the enrichment. Later on, Dupke & White (2000), based on

[3]This statement is more controversial in the case of low-mass systems (e.g. galaxy groups or giant ellipticals), where powerful galactic winds and active galactic nuclei outbursts might compete with the (somewhat) shallower gravitational potential well and uplift metals outside of the system.

[4]The equivalent width of a line is defined as the ratio of the line flux over the continuum flux at the position of the line.

ASCA observations of three clusters, favoured a dominant deflagration explosion channel for SNIa explosions. These two results, however, were challenged by more recent studies using the current generation of X-ray telescopes (e.g. Finoguenov et al. 2002; Böhringer et al. 2005; Werner et al. 2006b; de Plaa et al. 2006; Sato et al. 2007a). The most complete work has been done by de Plaa et al. (2007), who compiled the abundance measurements of 22 cool-core clusters observed by *XMM-Newton* and fitted their average abundance ratios with a combination of SNIa+SNcc models. They concluded that the measured abundance ratios: (i) favour the delayed-detonation channel for SNIa explosions; (ii) suggest that SNcc progenitors were previously enriched (i.e. have a positive initial metallicity); and (iii) show that Ca is overproduced with respect to the most common model predictions. Of course, such a study may now be further improved by compiling the abundance ratios of more (high- and low-mass) systems observed with deeper exposures, and by comparing these ratios with more recent supernova yield models, after carefully checking all the systematic uncertainties that may affect the results (see Chapters 3 and 4).

1.3.4 Stellar and intra-cluster phases of metals

As explained earlier, the baryonic content of galaxy clusters consists of two separate components: (i) the ICM and (ii) the stellar mass in (and between) galaxies. Whereas a significant fraction of the metals is somehow dispersed into the ICM (see also Sect. 1.3.5), the other part remains locked within the cluster galaxies, in particular in low- and intermediate-mass stars. In principle, such a fraction is simple to estimate on basis of the stellar luminosity (as a proxy of the stellar mass) and the assumed yields from SNIa and SNcc models. Several analytical works (Loewenstein 2013; Renzini & Andreon 2014, and references therein) estimate that there is at least as much Fe released into the ICM as there is still locked into stars. In massive clusters ($>10^{14}\ M_\odot$), this fraction seems to increase and may even pose a serious problem: there is 2 to 3 times too much Fe measured in the ICM compared to what could have been produced by all the stars in the cluster galaxies. A recent study based on semi-analytic simulations better conciliates the expected and measured Fe abundances in the ICM of the most massive clusters (Yates et al. 2017). However, a mismatch is still found in clusters of intermediate mass (too much metals compared to the predictions) and in groups (too few metals compared to the predictions). Clearly, the relation between absolute supernova yields and the metal content in groups and clusters is far from being solved.

Do the intra-cluster abundances really reflect the nucleosynthesis of all the stars and supernovae in galaxy clusters? This question is not trivial at all, but the answer is probably no, essentially for two reasons. First, comparing directly the ICM abundances with supernova yields implicitly assumes that all stars and supernovae create and disperse their products instantaneously after their formation[5]. In reality, SNcc and SNIa require significant and different delays before they could effectively enrich the ICM (Matteucci & Chiappini 2005). Second, it is likely that SNIa and SNcc are not dispersed into the ICM with the same efficiency. It is currently believed that SNcc products are preferentially locked up in stars while SNIa products are more easily released in the ICM (e.g. Loewenstein 2013). Ignoring these enrichment delays may lead to some incorrect interpretations, for example about the true ratio of all supernovae having exploded in clusters.

Although the ICM abundances may not be fully representative of the chemical composition produced at first place, they can still be correctly interpreted in terms of SNIa and SNcc having actually contributed to the ICM enrichment. Keeping this difference in mind, the ICM abundances can still be used to constrain SNIa and SNcc models.

1.3.5 Where and when was the ICM chemically enriched?

Whereas it is clear that metals present in the ICM ultimately originate from SNIa and SNcc having occurred within the cluster gravitational potential well, three major questions still arise:

- From which astrophysical sources does the bulk of the enrichment originate? The central BCG, late-type satellite galaxies, or intra-cluster stars?
- By which dominant mechanism(s) does a fraction of the metals escape their galactic gravitational potential wells and pollute the intra-cluster gas?
- At which step(s) of the cosmic time and/or cluster evolution do metals enrich the ICM?

Clearly, these questions are not trivial and require a deep synergy between theory, simulations, and observations in order to be solved. Generally speaking, the bulk of the enrichment has probably occurred around the peak of

[5]This assumption is also known as the "instantaneous recycling approximation".

cosmic star formation $z \sim 2$–3 (for a review, see Madau & Dickinson 2014), i.e. when the ICM started to form. More precisely, the observed spatial distribution of metals in clusters (whether from real observations or from snapshots of chemo-dynamical simulations) may provide useful hints and further constraints (Fig. 1.6) to these three above questions.

Since the discovery of a systematic central Fe enhancement in cool-core clusters up to about one solar in the centre (Allen & Fabian 1994; Fukazawa et al. 1994; De Grandi & Molendi 2001, see also Sect. 1.3.1), several studies showed that the Fe mass of this excess has been likely produced by SNIa belonging to the central BCG (Böhringer et al. 2004a; De Grandi et al. 2004). On the other hand, recent observations by *Suzaku* showed a remarkably uniform level of Fe enrichment in the outskirts of the Perseus cluster (Werner et al. 2013). The latter result has also been extended to other elements as well. This includes SNcc-dominated products, like Mg, among other elements in the outskirts of the Virgo cluster (Simionescu et al. 2015). Put together, these findings converge toward the picture of two major stages of enrichment (at least for cool-core clusters):

1. An early ($z \gtrsim 2$) enrichment which took place essentially before the cluster was well assembled, when metals created by both SNIa and SNcc had been released and efficiently mixed in the still forming ICM from star-forming galaxies via powerful galactic winds (see also below);

2. A later enrichment, presumably coming from SNIa in the central BCG, responsible for the central Fe excess in cool-core clusters.

Observational hints toward this picture also seem to corroborate the most recent cosmological simulations that take the cluster enrichment aspect into account (e.g. Planelles et al. 2014; Biffi et al. 2017).

In parallel, several chemo-dynamical simulations investigated the relative role of the possible mechanisms that could be responsible for the galactic escape of metals into the ICM (for a review, see Schindler & Diaferio 2008). Among them, two dominant channels seem to be favoured: (i) ram-pressure stripping, occurring when an infalling galaxy gets its interstellar gas stripped by the pressure of the ambient ICM (Gunn & Gott 1972) and (ii) galactic winds or outflows provided by the total kinetic energy of the supernova explosions (De Young 1978). While ram-pressure stripping is more efficient in cluster cores, where the ICM pressure is more important and the gravitational potential more efficient to attract galaxies, galactic

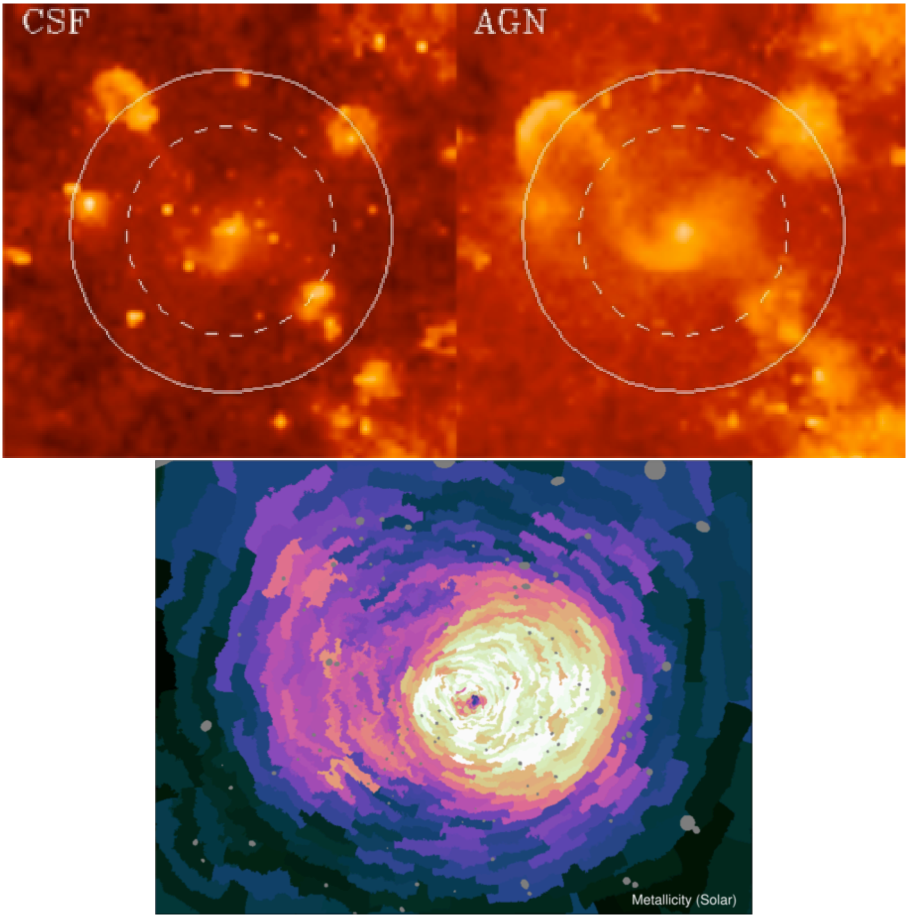

Figure 1.6: *Top:* Simulated maps of the (emission-weighted) Fe distribution in a massive cluster (Planelles et al. 2014). The "CSF" case (left panel) includes the effects of radiative cooling, star formation, and supernova feedback, while the "AGN" case (right panel) also accounts for AGN feedback. The typical radii r_{180} and r_{500} are indicated by the continuous and dashed white circles, respectively. The colour coding ranges between 0.02 solar (black) to 1.87 solar (light yellow). *Bottom:* Observed map of the (projected) Fe distribution in the Centaurus cluster (Sanders et al. 2016). The colour coding ranges between 0 solar (dark purple) to 1.7 solar (light yellow). The map extends to $\sim 0.07 r_{500}$.

winds take a larger role in cluster outskirts (and presumably at earlier cosmic times), where there is less resistance of the ambient ICM to spread out the metals and when the star-forming activity in galaxies was more important than at present times (see also above). Note that other processes, such as galaxy-galaxy interaction, outflows from active galactic nuclei (AGN), or enrichment by the intra-cluster stars may also contribute to the ICM enrichment, although probably to a less significant extent (Schindler & Diaferio 2008).

Despite all these significant progresses, many uncertainties on the full cluster enrichment picture still remain. For instance, due to their very low signal-to-noise obtained by the current generation of X-ray telescopes, cluster outskirts are left widely unexplored. For a recent review on cluster outskirts, see Reiprich et al. (2013). Moreover, the current instrumental limitations also prevent us from studying in detail the amount and spatial distributions of metals in high-redshift clusters ($z \gtrsim 0.5$). Last but not least, even in nearby clusters past and recent studies of individual objects or small samples did not converge toward a consistent radial distribution for SNcc products (O, Mg, Si, etc.; e.g. Werner et al. 2006a; Simionescu et al. 2009b; Lovisari et al. 2011), leaving questions on the role of SNcc in enriching the central parts of clusters and groups.

1.4 Spectral codes for a collisional ionisation equilibrium plasma

As mentioned in Sect. 1.3.3, the derivation of chemical abundances in the ICM from the equivalent widths of their corresponding emission lines is in principle straight forward. However, it clearly requires a good knowledge of all the subsequent emission processes responsible for both the line and the continuum spectral components. In other words, the use of proper spectral models with up-to-date atomic databases is crucial to correctly derive and interpret the ICM abundances.

Historically, the first atomic code reproducing X-ray spectra of hot, optically thin plasmas in CIE was calculated by Cox & Tucker (1969). After this pioneering work, and thanks to the increasing computing performance since the 1970's, essentially two atomic codes were built and then continuously updated up to now.

The first one was initially written by Mewe (1972), and after some updates (Mewe et al. 1985, 1986) became a reference for many years (abbreviated as the "Mewe-Gronenschild" code). The code was later updated first as the `meka` code (following it main contributors: Rolf Mewe and Jelle Kaastra), and then as the `mekal` code (Rolf Mewe, Jelle Kaastra, Duane Liedahl) in 1995. It was incorporated into the XSPEC fitting package[6] (Arnaud 1996). Since 1995, the code (renamed `cie`) has been continuously updated as part of its own fitting package, SPEX[7] (Kaastra et al. 1996), with two major updates, in 1996 and in 2016 (see Chapter 5). SPEX (and its available single- and multi-temperature CIE models) is the code that is used throughout this thesis.

The second one was initially written by Raymond & Smith (1977) and had been widely used by the X-ray community, together with the Mewe-Gronenschild code. Later on, the code was updated (Smith et al. 2001; Brickhouse & Smith 2005) and became part of the atomic database AtomDB[8]. This spectral model (and atomic database) is also known as the `apec` model as part of XSPEC, and is still regularly updated.

1.5 This thesis

As we have seen in the previous sections, despite considerable progress in the determination of abundances in the ICM and their interpretation as a chemical enrichment from SNIa and SNcc over the largest scales of the Universe, many intriguing questions on supernovae or on the chemical enrichment itself remain to be solved. Obviously, tackling all the aspects of the ICM enrichment would probably take several decades of future efforts. Nevertheless, in this thesis I focus on two particular questions, closely related to what has been discussed in Sect. 1.3.3 and 1.3.5:

1. What do the elemental abundances measured in the ICM cool cores tell us about the intrinsic physics and environmental conditions of the billions of supernovae that exploded and produced these elements?

2. What do the observed spatial distribution of elemental abundances in the cool-core ICM tell us about the main epoch(s) and production sites of the enrichment?

[6]http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec
[7]https://www.sron.nl/astrophysics-spex
[8]http://www.atomdb.org/index.php

This thesis is essentially based on a large sample of *XMM-Newton* observations of 44 cool-core galaxy clusters, groups, and ellipticals (the CHEmical Enrichment Rgs Sample, or CHEERS), with a total net exposure of $\sim$4.5 Ms (de Plaa et al. 2017). This is the first time that the ICM enrichment is studied over such a large sample and such a deep total exposure. The CHEERS sample combines new very deep observations of 11 systems with archival data of other clusters and groups. The selection of the objects of the sample are based on a $>5\sigma$ significance of the detection of the O VIII 1s–2p emission line at 19 Å with the RGS instrument. For further details on the CHEERS project, see de Plaa et al. (2017). In addition to ensuring optimal constraints on the SNcc enrichment, the instrumental detection of the O VIII line in the ICM is a good indicator or the reasonable detectability of the other main metal lines. Because line emissivities are larger in cooler plasmas and because cool-core clusters are more compact, hence produce higher resolution RGS spectra, all the objects in our sample are cool-core[9].

The outline of this thesis is structured as follows.

Chapter 2 is devoted to the full *XMM-Newton* analysis of Abell 4059, a galaxy cluster which is part of the CHEERS sample. A careful treatment of the background is detailed, and is applied to the analysis of all the other objects in the next chapters. Abell 4059 is a textbook example that clear asymmetries can be found in the metal distribution of galaxy clusters, and that ram-pressure stripping might sometimes play a significant role in enriching the central regions of the ICM.

In **Chapter 3**, I present the individual abundances of all the CHEERS objects within a consistent radius, $0.05r_{500}$[10], as well as within $0.2r_{500}$ when possible. I discuss extensively several systematic uncertainties that could be associated with our measurements. Then, I stack the individual measurements to build an average abundance pattern, representative of the enrichment in the ICM as a whole. Doing so, I also report constraints on the average Cr/Fe ratio and, for the very first time, the presence of Mn in the ICM.

Chapter 4 constitutes the immediate follow-up of Chapter 3, as well as a central point of this thesis. I interpret the previously derived ICM

[9] A similar study could be done on non-cool-core systems, although this would probably require even deeper exposures, and would be limited to less massive systems exhibiting reasonable central temperatures.

[10] Used as a common way to define astrophysically consistent sizes in galaxy clusters and groups, r_{500} defines the radius within which the cluster/group total density reaches 500 times the critical density of the Universe.

abundance pattern in terms of enrichment by SNIa and SNcc. By fitting the CHEERS data to various supernova yield models, I attempt to provide independent constraints on (i) the IMF and initial metallicity of the average population of the SNcc progenitors; (ii) the favoured channels driving SNIa explosions as well as the dominant nature of SNIa progenitors; and (iii) possible initial enrichment by metal poor (or Population III) stars, or hypernovae.

Chapter 5 is the updated version of Chapters 3 and 4, and corrects the previous results from a major update in the spectral models and atomic databases used to fit the X-ray spectra (SPEX). From a more global perspective, this chapter deals with the impact of atomic uncertainties on the interpretations of the ICM enrichment.

While Chapters 3, 4, and 5 essentially focus on the integrated supernova yields in the central cluster cool cores, in **Chapter 6** I use the CHEERS sample to establish radial abundance profiles in cool-core systems, and interpret them in term of enrichment sources and history.

Finally, **Chapter 7** concludes this thesis by discussing the current limitations in this field and the bright (although still somewhat far) future that the next generation of X-ray missions will offer.

Toeval is logisch.

Coincidence is logical.

– Johan Cruijff