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On the influence of high energy electron populations on metal abundance estimates in galaxy groups and clusters

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ABSTRACT

Aims. Spectral line emissivities have usually been calculated for a Maxwellian electron distribution. But many theoretical works on both galaxy groups and clusters and the solar corona consider modified Maxwellian electron distribution functions when fitting observed X-ray spectra. Here we examine the influence of high energy electron populations on measurements of metal abundances.

Methods. A generalized approach proposed by ourselves is used to calculate the line emissivities for a modified Maxwellian distribution. We study metal abundances in galaxy groups and clusters in which hard X-ray excess emission was observed.

Results. We found that for modified Maxwellian distributions the argon abundance decreases for the HCG 62 group, the iron abundance decreases for the Centaurus cluster, and the oxygen abundance decreases for the solar corona with respect to the case of a Maxwellian distribution. Therefore, metal abundance measurements are a promising tool for testing the presence of high energy electron populations.

Key words. galaxies: clusters: general – atomic processes – radiation mechanisms: non-thermal

1. Introduction

Galaxy clusters are large structures in the Universe, with radii of the order of a megaparsec. Groups of galaxies are the poorest class of galaxy clusters. The space between galaxies in clusters is filled with low-density $\sim 10^{-3}$ cm^{-3} high temperature ($k_{\rm B}T \sim 1{-}10$ keV) gas (for a review, see e.g., Sarazin 1986). The temperatures of 1–10 keV are close to the values of the K-shell ionization potentials ($I_Z = Z^2 Ry$, where Z is the atomic number and Ry is the Rydberg constant) of heavy elements with atomic numbers in the range of $Z = 10$–26.

Emission lines from heavy elements were detected by X-ray telescopes from galaxy groups and clusters. The current instruments (XMM-Newton, Chandra, and Suzaku) have provided precise measurements of the chemical abundances of many elements (O, Ne, Mg, Si, C, Ar, Ca, Fe, and Ni) in groups and clusters. Metal abundances of around 0.5 in the solar units of Anders & Grevesse (1989) are derived based on the assumptions of collisional equilibrium (for a review, see Werner et al. 2008).

The ionization rates, recombination rates, and emissivity in a spectral line have usually been calculated for a Maxwellian electron distribution (e.g., Mewe & Gronenschild 1981). However, in many low-density astrophysical plasmas, the electron distribution may differ from a Maxwellian distribution (e.g., Porquet et al. 2001).

Hard X-ray tails reported in BeppoSAX X-ray spectra of some galaxy clusters (Fusco-Femiano et al. 1999; Fusco-Femiano et al. 2004; Rossetti & Molendi 2004, for the Coma cluster; Kaastra et al. 1999, for the Abell 2199; Molendi et al. 2002 for the Centaurus cluster) were interpreted as bremsstrahlung emission from non-thermal subrelativistic electrons (see e.g., Sarazin & Kempner 2000) or from thermal electrons with a Maxwellian spectrum distorted by a particle acceleration mechanism (Blasi 2000; Liang et al. 2002; Dogiel et al. 2007). The bremsstrahlung interpretation is associated with a huge energy output of emitting particles and faces energetics problems (e.g., Petrosian 2001). Evidence of a hard X-ray excess above the thermal emission was also discovered in galaxy groups with ASCA (Fukazawa et al. 2001; Nakazawa et al. 2007). The evidence and nature of hard X-ray spectral tails in these galaxy groups and clusters are discussed in the review by Rephaeli et al. (2008).

The use of non-extensive thermo-statistics (Tsallis 1988, for a review, see Tsallis 1999), based on the natural generalization of entropy for systems with long-range interactions, was proposed by Hansen (2005) to fit the X-ray spectrum observed near NGC 4874 (close to the center of the Coma cluster). We consider non-extensive thermo-statistics as another approach to explaining hard X-ray excess in groups and clusters in the framework of the bremsstrahlung model.

A more traditional interpretation of hard X-ray tails based on the inverse Compton scattering (ICS) of relativistic electrons on relic photons (Sarazin & Lieu 1998) faces a serious problem. The combination of hard X-ray and radio observations within the ICS model infers a magnetic field strength that is much lower than that derived from Faraday rotation measurements (e.g., Clarke et al. 2001). Several arguments have been proposed to explain (at least in part) this disagreement (for a review, see Brunetti 2003; Ferrari et al. 2008; Petrosian et al. 2008a).

The presence of high energy subrelativistic electrons (non-thermal subrelativistic electrons or thermal electrons with a Maxwellian spectrum distorted by the particle acceleration mechanism) or the use of non-extensive thermo-statistics must be probed using various observational methods to test the various interpretations of X-ray tails from galaxy clusters.

The Sunyaev-Zel'dovich (SZ) effect can be used to constrain the electron distribution in galaxy clusters. The influence of high energy subrelativistic electrons on the SZ effect was studied for the Coma and Abell 2199 clusters by Blasi et al. (2000) and Shimon & Rephaeli (2002). A method based on the measurement of the spectral slope around the crossover frequency of the SZ effect was proposed by Colafrancesco et al. (2009) to analyze the high energy electron populations in galaxy clusters.

A new probe to study the electron distribution in galaxy clusters, namely the flux ratio of the emission lines due to FeKα transitions (FeXXV and FeXXVI) was considered by Prokhorov et al. (2009). This flux ratio is very sensitive to the population of electrons with energies higher than the ionization potential of a FeXXV ion (which is ≈8.8 keV). The influence of the high energy subrelativistic electron population on the flux ratio is more prominent in low temperature clusters (such as Abell 2199) than in high temperature clusters (such as Coma), because the fraction of thermal electrons with energies higher than the helium-like iron ionization potential in low temperature clusters is smaller than that in high temperature clusters. However, the FeXXVI line is weak in low temperature clusters and current instruments do not have sufficient sensitivity to measure the iron line flux ratio.

Kaastra et al. (2009) demonstrated that the relative intensities of the satellite lines are sensitive to the presence of supra-thermal electrons in galaxy clusters and that the instruments on future missions such as Astro-H and IXO will be able to identify either the presence or absence of these supra-thermal electrons.

In this paper, we study the influence of high energy electron populations on metal abundance estimates in galaxy groups and clusters and show that the effect of high energy particles can be significant. This effect is a promising test of the presence of high energy subrelativitic electrons in galaxy groups and clusters because of substantial changes in abundance estimates for modified Maxwellian distributions. We also consider the effect of high energy electrons on abundance estimates in the solar corona where the presence of modified Maxwellian electron distributions has been proposed.

The paper is organized as follows. In Sect. 2.1, we choose a galaxy group and a galaxy cluster, where high energy subrelativistic electron populations have been proposed and derive values of the electron distribution parameters. We calculate the changes in metal abundances with respect to the values for a Maxwellian distribution in Sect. 2.2. We discuss the bremsstrahlung model of hard X-ray emission from galaxy clusters in Sect. 3 and present our conclusions in Sect. 4. We calculate an oxygen abundance decrease in the solar corona in Appendix A.

2. Metal abundances in groups and clusters with a high energy electron population

Metal abundances are usually derived based on the assumption of a Maxwellian electron distribution. We consider the influence of high energy subrelativistic electron populations on metal abundance determinations.

2.1. High energy subrelativistic electron populations in galaxy groups and clusters

Since we wish to analyze the influence of a high energy subrelativistic electron population on abundance estimates of chemical elements with atomic numbers $Z \leqslant 26$, we must consider cool clusters where the influence of high energy subrelativistic electrons on impact excitation and ionization is more important.

The two objects considered below are the HCG 62 group and the Centaurus cluster, with respective temperatures of 1 keV and 3.5 keV. These objects are interesting because of hard X-ray excess detections by Fukazawa et al. (2001) and Molendi et al. (2002), suggesting a possible high energy subrelativistic electron component if these hard X-ray excesses are interpreted in terms of bremsstrahlung emission.

The HCG 62 group is a bright group of galaxies at a redshift $z = 0.0146$. The best-fit model temperature is $kT = 0.95 \pm 0.03$ keV in the energy band below 2.5 keV (Nakazawa et al. 2007). A hard X-ray excess from this galaxy group was discovered by Fukazawa et al. (2001). The highly significant hard X-ray signal in the energy band 4.0–8.0 keV, of which only ∼25% can be accounted for by thermal IGM (intragalactic medium) emission, was reconfirmed by Nakazawa et al. (2007). Abundances of Mg, Si, S, and Fe were obtained with Suzaku by Tokoi et al. (2008).

The Centaurus cluster (Abell 3526) is amongst the nearest ($z = 0.0114$) and brightest clusters in the X-ray sky. Its average gas temperature is $kT = 3.6 \pm 0.1$ keV (Molendi et al. 2002). Molendi et al. (2002) detected a hard X-ray excess at the 3.6σ level and concluded that it is impossible from the Beppo-SAX PDS data alone to establish the origin of this emission. The abundances of chemical elements in the Centaurus cluster were studied by Molendi et al. (2002) and Fabian et al. (2005).

To interpret hard X-ray spectral tails in the framework of the bremsstrahlung model, different electron distributions have been proposed (e.g., Dogiel 2000; Sarazin & Kempner 2000; Dogiel et al. 2007). Sarazin & Kempner (2000) assumed that the supra-thermal electron populations have an electron kinetic energy of at least $3kT$, where T is the temperature of the intracluster medium (ICM). This electron distribution was considered by Shimon & Rephaeli (2002) when analyzing of the influence of supra-thermal electrons on the SZ effect and by Prokhorov et al. (2009) when analyzing electron distributions by means of the flux ratio of iron lines FeXXV to FeXXVI. In this case, the electron distribution function is given by

$$f_1(x) = f_{\rm M}(x), \quad x < 3 \qquad (1)$$
$$f_1(x) = f_{\rm M}(x) + \lambda x^{-(\mu+1)/2}, \quad x \geq 3$$

where $x = E/kT$, $f_{\rm M}(x)$ is a Maxwellian function, $\mu = 3.33$ is taken from Sarazin & Kempner (2000) and the normalization coefficient λ is calculated from observational data. For the calculations of the ionization, excitation, and recombination rates, the electrons with very high energies (≥20 kT) have negligible effect (Porquet et al. 2001), therefore we can place the cut-off at any energy above that of 20 kT without changing the line emissivities.

Another approach to fitting X-ray spectra of galaxy clusters in the framework of the bremsstrahlung model was proposed by Hansen (2005). He considered the ICM in thermodynamical equilibrium, but with an electron distribution function defined by means of non-extensive thermo-statistics (Tsallis 1988). The reasons for using Tsallis statistics in galaxy clusters are discussed in Sect. 4 of Hansen (2005). The equilibrium distribution function in non-extensive thermo-statistics (e.g., Silva et al. 1998) is

$$f_2(x) = C\sqrt{x}\,(1-(q-1)x)^{1/(q-1)}, \qquad (2)$$

where C is the normalization constant and q is the parameter quantifying the degree of non-extensivity. The electron distribution $f_2(x)$ has the same form as a Kappa-distribution, which is frequently interpreted as a consequence of acceleration mechanisms in the solar corona (Leubner 2004).

We now attempt to find values of the distribution parameters λ (see Eq. (1)) and q (see Eq. (2)) from the ASCA data for the HCG 62 group and from the Beppo-SAX data for the Centaurus cluster:

1. For the HCG 62 group, Fukazawa et al. (2001) used the observed luminosity ratio of the non-thermal to thermal X-ray continuum components and the non-thermal bremsstrahlung model (Kempner & Sarazin 2000) to estimate that the non-thermal electron population is 6% of the thermal electron population (the non-thermal electron energy density is 25% of the thermal electron energy density). We obtain the values of $\lambda = 0.28$ and $q = 0.97$ by integrating over the electron spectra $f_1(x)$ and $f_2(x)$, respectively.
2. For the Centaurus cluster, the total luminosity of the non-thermal component in the 20–200 keV band was calculated by Molendi et al. (2002) from a Beppo-SAX observation. Molendi et al. (2002) considered the bremsstrahlung model as a possible way of explaining the hard X-ray excess. The luminosity in the 2–10 keV band was calculated by Fabian et al. (2005). From the observational data, we estimate that the non-thermal electron population is 5% of the thermal electron population (the non-thermal electron energy density is 21% of the thermal electron energy density) and obtain the values of $\lambda = 0.25$ and $q = 0.975$ by integrating over the electron spectra $f_1(x)$ and $f_2(x)$, respectively.

We note that supra-thermal electron populations that represent 4% and 8% of the thermal electrons were also proposed by Sarazin & Kempner (2000) as constituents of the Coma and Abell 2199 clusters, respectively.

Evidence of non-thermal X-rays in galaxy clusters remains controversial (e.g., Rossetti & Molendi 2004; Kitaguchi et al. 2007). The Suzaku observation of the Coma cluster does not provide evidence of non-thermal excess in the central region of the Coma cluster (Wik et al. 2009). An analysis of Suzaku XIS and HXD measurements of HCG 62 provided an upper limit to the non-thermal emission (Tokoi et al. 2008), but at a level that does not exclude the ASCA result.

The influence of the derived high subrelativistic electron populations on the metal abundance estimates is now considered in Sect. 2.2.

2.2. The influence of high energy electron populations on metal abundance estimates.

We now show that the effect of high energy subrelativistic electrons on hydrogen-like and helium-like emission lines can be significant. A generalized approach to calculating the emissivity in hydrogen-like and helium-like spectral (iron) lines for a modified Maxwellian electron distribution was given by Prokhorov et al. (2009). In this section, we propose to study the sum of the H-like and He-like line volume emissivities (in units of photons $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$) instead of the line volume emissivity ratio.

The sum of the H-like and He-like line volume emissivities for a chemical element of atomic number Z can be written as

$$\varepsilon_Z = n_e n_H A_Z \times (\xi_{Z-2} Q_{Z-2} + \xi_{Z-1} Q_{Z-1} + \xi_{Z-1}\alpha_{Z-2} + \xi_Z \alpha_{Z-1}), \quad (3)$$

where n_e is the electron number density, n_H is the H ionic number density, A_Z is the abundance of the considered chemical element, ξ_{Z-2} and ξ_{Z-1} are the ionic fractions of He-like and H-like ions, respectively, Q_{Z-2} and Q_{Z-1} are the impact excitation rate coefficients, and α_{Z-2} and α_{Z-1} are the rate coefficients for the contribution from radiative recombination to the spectral lines for a He-like triplet and H-like doublet, respectively.

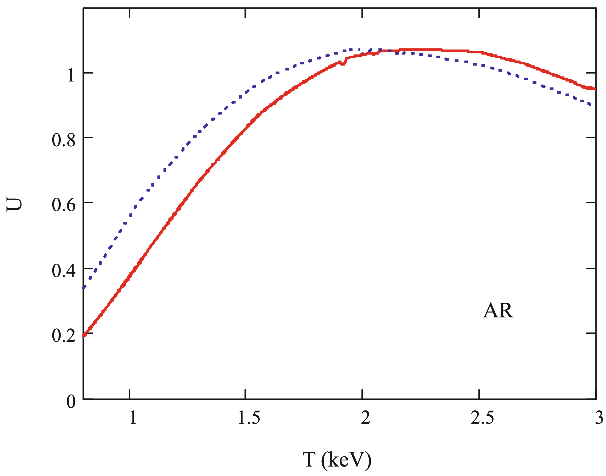

Fig. 1. Reduced argon emissivity U of both a Maxwellian electron distribution (solid line) and a modified Maxwellian distribution $f_1(x)$ (dashed line) for the HCG 62 group.

By U, we denote the reduced expression for the sum of emissivities ε_Z defined as

$$U = \frac{\xi_{Z-2} Q_{Z-2} + \xi_{Z-1} Q_{Z-1} + \xi_{Z-1}\alpha_{Z-2} + \xi_Z \alpha_{Z-1}}{\Gamma}, \quad (4)$$

where $\Gamma = Z^{-4}\pi a_0^2 \sqrt{I_Z/m_e}$ corresponds to the characteristic rate coefficient value, m_e is the electron mass, a_0 is the Bohr radius, and I_Z is the K-shell ionization potential.

For the sake of clarity, we consider the electron distribution $f_1(x)$ in more detail because of its distinct non-thermal power-law component at $x \geq 3$. In this case, the non-thermal electrons have energies higher than $3kT$, which correspond to the energies $E_{\mathrm{HCG62}} = 3$ keV and $E_{\mathrm{A3526}} = 10.5$ keV of the HCG 62 group and the Centaurus cluster (Abell 3526), respectively. Ionic fractions are very sensitive to the electron population with energies higher than the K-shell potential I_Z, therefore ions of argon $I_{Z=18} = 4.4$ keV and iron $I_{Z=26} = 9.2$ keV are promising targets for our analysis of the electron distributions in the HCG 62 group and the Centaurus cluster, respectively.

In the analysis of the reduced emissivity U, we use the method proposed by Prokhorov et al. (2009) to take into account the influence of the high energy subrelativistic electron population on the He-like and H-like line emissivities. All the necessary coefficients for calculating the direct ionization cross-sections are taken from Arnaud & Rothenflug (1985), the radiative recombination rates are taken from Verner & Ferland (1996), and the dielectronic recombination rates are taken from Mazzotta et al. (1998). We note that the fraction of Li-like ions of Ar at temperatures $kT \geq 1$ keV is less than 5% and the fraction of Li-like ions of Fe at temperatures $kT \geq 3.5$ keV is less than 12% (e.g. Mazzotta et al. 1998). We included the Li-like ion fractions in the analysis of the ionization balance.

In Fig. 1, we compare the reduced argon emissivity of the Maxwellian electron distribution with that of the modified Maxwellian electron distribution $f_1(x)$, which has a fraction of high energy subrelativistic electrons equal to 6% as in the HCG 62 group.

For the HCG 62 group ($kT = 1$ keV), the reduced emissivity U of a modified Maxwellian distribution $f_1(x)$ increases by ≈49% with respect to the case of a Maxwellian distribution. This

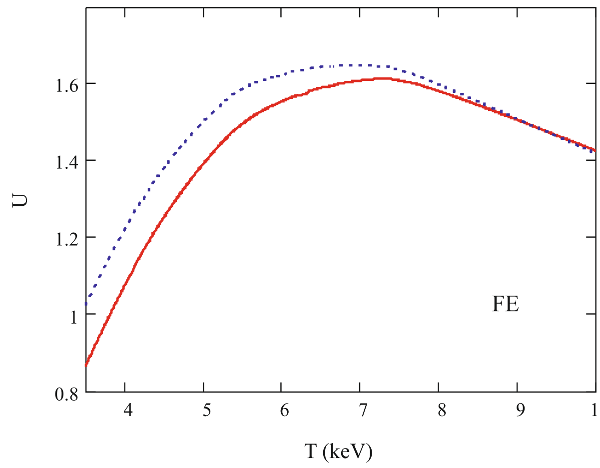

Fig. 2. Reduced iron emissivity U of both a Maxwellian electron distribution (solid line) and a modified Maxwellian distribution $f_1(x)$ (dashed line) for the Centaurus cluster.

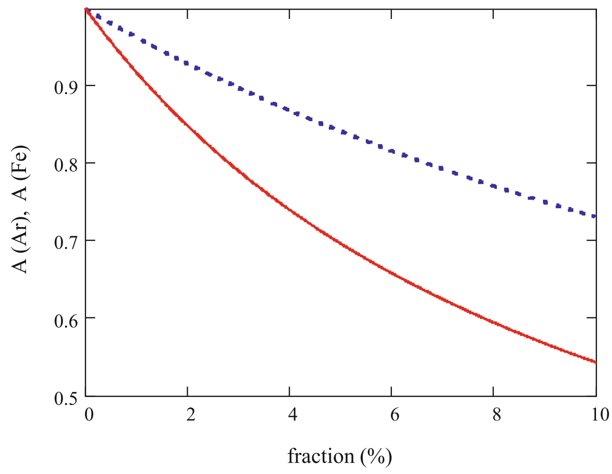

Fig. 3. The solid (dashed) line shows the dependence of the ratio of the argon (iron) abundances of a modified Maxwellian distribution to that of a Maxwellian distribution on the fraction of high energy electrons.

increase in the reduced emissivity U corresponds to a decrease in the argon abundance $A_{Z=18}$ of a constant value of $\varepsilon_{Z=18}$ (see Eq. (3)). For a modified Maxwellian distribution $f_1(x)$, the argon abundance decreases by ≈33% with respect to the case of a Maxwellian distribution. The decrement of the argon abundance for a modified Maxwellian distribution $f_2(x)$ is 27%.

Abundances of Mg, Si, S, and Fe in the HCG 62 group were calculated from Suzaku data by Tokoi et al. (2008), but the expected Ar abundance is 4.5 times lower than the S abundance (Anders & Grevesse 1989) and it is more difficult to detect Ar lines. The predicted decrease in the Ar abundance is a tool for testing the bremsstrahlung interpretation of the hard X-ray tail in HCG 62.

The Centaurus cluster is another interesting object of study. In Fig. 2, we compare the reduced iron emissivity of a Maxwellian electron distribution with that of a modified Maxwellian electron distribution $f_1(x)$ with a fraction of high energy subrelativistic electrons equal to 5%, as in the Centaurus cluster. We found that the iron abundance of the modified Maxwellian distributions $f_1(x)$ and $f_2(x)$ decreases by ≈15% and ≈13%, respectively, with respect to the case of a Maxwellian distribution.

We also calculated changes in the abundance estimates of the chemical elements closest in atomic numbers to Ar and Fe and found that: 1) for HCG 62, the Si abundance increases by 3%, and the S abundance decreases by 14%; 2) for the Centaurus cluster, the Ar abundance increases by 2%, and the Ca abundance increases by 0.5%.

High energy subrelativistic electrons create a higher apparent temperature. If the gas temperature is lower than the temperature at which the reduced emissivity U of the chemical element has a maximum value, then the abundance estimate decreases because of an increase in the reduced emissivity with temperature at these temperatures. However, if the gas temperature is higher than the temperature at which the reduced emissivity U of the chemical element has its maximum value, then the abundance estimate increases.

We now demonstrate how the argon and iron abundances inferred from X-ray observations yield important constraints on the fraction of high energy electrons. For this purpose, synthetic clusters with temperatures of 1 and 3.5 keV (as in the HCG 62 group and in the Centaurus cluster) and an electron distribution function $f_1(x)$ are considered. The dependences of both argon and iron abundance ratios of both a modified Maxwellian distribution and a Maxwellian distribution on the fraction of high energy subrelativistic electrons are shown in Fig. 3. We conclude that high energy electron populations can affect derived the metal abundances of the HCG 62 group and the Centaurus cluster.

3. Discussion

We can assume, in addition to the bremsstrahlung-emitting thermal ICM and synchrotron-emitting, relativistic, non-thermal electrons, that a high energy subrelativistic population of electrons emits a hard X-ray excess as bremsstrahlung.

There are three possible origins of high energy subrelativistic populations: non-thermal (Sarazin & Kempner 2000), quasi-thermal (Blasi 2000; Dogiel 2000; Liang et al. 2002; Dogiel et al. 2007; Wolfe & Melia 2008), and thermal in the framework of the non-extensive thermo-statistics (Hansen 2005). Since line emissivities depend on the fraction of high energy electrons (e.g., Prokhorov et al. 2009) and do not depend on the origin of these electrons, we can use the electron distribution $f_1(x)$ to calculate line emissivities in the cases of the non-thermal and quasi-thermal electron origins.

Petrosian (2001) estimated the yield in non-thermal bremsstrahlung photons $Y \sim (\mathrm{d}E/\mathrm{d}t)_{\mathrm{br}}/(\mathrm{d}E/\mathrm{d}t)_{\mathrm{c}} \sim 10^{-5}$. Here $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{br}}/(\mathrm{d}E/\mathrm{d}t)_{\mathrm{c}}$ is the ratio of bremsstrahlung to Coulomb losses of non-thermal electrons. For a hard X-ray flux $F_{\mathrm{x}} \sim 10^{43}$ erg/s, a large amount of the energy of the non-thermal electrons $F_{\mathrm{e}} \sim F_{\mathrm{x}}/Y \sim 10^{48}$ erg/s is transmitted to the background plasma. As a result, the ICM should be heated to above its observable temperature within 10 Myr (Petrosian 2001; Wolfe & Melia 2006).

However, it was shown by Liang et al. (2002) and Dogiel et al. (2007) that a quasi-thermal electron population might overcome this difficulty by means of a higher radiative efficiency (and therefore a longer overheating time, but see Petrosian & East 2008). The energy supply necessary to produce the observed hard X-ray flux by quasi-thermal electrons is at least one or two orders of magnitude smaller (Dogiel et al. 2007) than derived from the assumption of a non-thermal origin of emitting electrons. Wolfe & Melia (2008) also considered a quasi-thermal electron distribution when fitting hard X-ray emission, but rather than requiring a second-order Fermi acceleration to produce the quasi-thermal electrons, they assumed that quasi-thermal electrons are produced by collisions with non-thermal protons.

4. Conclusions

We have shown that metal abundance estimates depend on the presence of high energy subrelativistic electrons proposed to account for the measurements of hard X-ray excess emission from galaxy groups and clusters. Because of the impact of these energetic electron populations, the Ar abundance estimate in the HCG 62 group and the Fe abundance estimate in the Centaurus cluster decrease significantly by ≈30 and ≈15%, respectively.

These decreases in the Ar and Fe abundance estimates are determined by the high energy subrelativistic electron fractions (6% for the HCG 62 group and 5% for the Centaurus cluster), which are comparable to the thermal electron fractions for energies higher than the K-shell ionization potentials of Ar and Fe, respectively.

The influence of the high energy subrelativistic electron populations on the abundance estimates is measurable with current instruments. Therefore, this probe is more efficient for detecting the high energy subrelativistic electron populations than that based on the Doppler broadening of the spectral lines proposed by Hansen (2005), which requires very high energy resolution, or that based on the flux ratio of the emission lines (Prokhorov et al. 2009), which requires higher sensitivity instruments.

Other possibilities for producing the change in the metal abundance estimates in galaxy clusters are the effect of resonant scattering (Gilfanov et al. 1987) and the presence of multiphase hot gas – two temperature model (Buote & Fabian 1998; Buote 2000).

The effect of resonant scattering causes the decrement of the FeXXV line at 6.7 keV, and, therefore, the decrement of the flux ratio of the iron lines FeXXV/FeXXVI. A decrement in the Fe abundance is then produced, as in the case of a high energy subrelativistic electron population. To separate the effects of resonant scattering and the high energy subrelativistic population influence, the SZ effect from a high energy subrelativistic population can be analyzed. Following the method of Colafrancesco et al. (2009), we calculated the value of the slope of the SZ effect in the Centaurus cluster. We obtained the value of the slope $S \approx 0.033$ for both electron distributions $f_1(x)$ and $f_2(x)$ and the value of the slope $S \approx 0.028$ for a Maxwellian spectrum. Since the slope equals $S \approx 4.25 \times kT/(m_e c^2)$ for a Maxwellian electron spectrum without a high energy subrelativistic electron population (Colafrancesco et al. 2009), the value of the slope of $S = 0.033$ corresponds to that of an effective temperature $kT = 4.5$ keV, which is higher than the temperature $kT = 3.5$ keV observed with Beppo-SAX.

Buote (2000) analyzed the ASCA data for the HCG 62 group, the same as the data analyzed by Nakazawa et al. (2007), and fitted the spectrum in the frame of a two-temperature model with temperatures $kT_1 = 0.7$ keV and $kT_2 = 1.4$ keV. Nakazawa et al. (2007) showed that the spectrum of the HCG 62 group is reproduced well by the two-temperature model of Buote (2000) in the energy range below ~4 keV, but a fit to the full spectrum requires a thermal component with an unrealistically high temperature of ~17.5 keV.

We have shown that high energy electron populations can affect the derived metal abundances in galaxy groups and clusters and in the solar corona. Therefore, metal abundances are a promising tool for analyzing the high energy subrelativistic electron component.

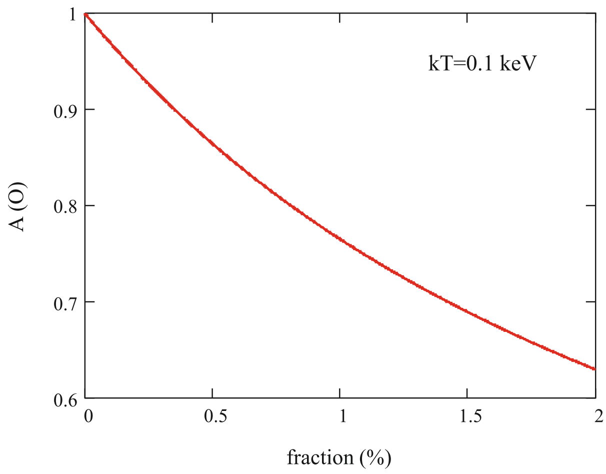

Fig. A.1. Dependence of the ratio of the oxygen abundances of both a modified Maxwellian distribution and a Maxwellian distribution on the fraction of high energy electrons.

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Appendix A: Oxygen abundance sharp decrease inside the solar corona

Often the particle distribution functions in space plasmas, e.g., solar corona plasma, are observed to be quasi-Maxwellian at the mean thermal energies, while they have non-Maxwellian suprathermal tails at higher energies (e.g., Porquet et al. 2001). A Kappa-distribution is very convenient for modelling these particle distribution functions, since it fits both the thermal and suprathermal parts of the observed energy spectra (for a review, see Leubner 2004).

The ionization and excitation rates for the elements C, O, and Fe for a Kappa-distribution of electrons in the solar corona were studied by Owocki & Scudder (1983) and Dzifcakova & Kulinova (2001, 2003).

We now demonstrate how the oxygen abundance inferred from X-ray observations yields important constraints on the fraction of high energy electron populations. For this purpose, a plasma with temperature $kT = 0.1$ keV (as in the solar corona) and an electron distribution function $f_2(x)$ are considered. The dependence of the ratio A(O) of the oxygen abundances of both a modified Maxwellian distribution and a Maxwellian distribution on the fraction of high energy subrelativistic electrons is shown in Fig. A.1. Because of the impact of high energy subrelativistic electrons, the oxygen abundance estimate in the solar corona significantly decreases. Even if the fraction of high energy electrons is only 1%, the decrease in the oxygen abundance is about 30%.

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