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COLLISIONAL IONIZATION

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COLLISIONAL IONIZATION

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1 - INTRODUCTION

In low density, thin plasmas (such as stellar coronae, interstellar medium, intracluster medium) the ionization process is governed by collision between electrons and ions in their ground state. Photoionization may be neglected as far as no external ionizing flux is present.

Two processes are involved in collisional ionization:

1. direct ionization

$$X_Z^j + e^- \rightarrow X_Z^{j+1} + e^- + e^-$$

where X_Z^j is the j times ionized element of nuclear charge Z.

1. excitation-autoionization

$$X_Z^j + e^- \xrightarrow{\text{collisional excitation}} X_Z^{j*} + e^-$$

$$X_Z^{j*} \xrightarrow{\text{autoionization}} X_Z^{j+1*} + e^-$$

a collisional excitation of an innershell electron may be followed by auto-ionization if the excitation energy is greater than the first ionization potential of the ion. This process may be a large contributor to the total ionization rate for isoelectronic sequences with a large number of innershell electrons and only 1 or 2 outer electrons (Li-like ions, Na-like ions ...)

In low density plasmas the ionization cross section $\sigma_{Z,j}(v)$ only depends on the relative velocity v between the ion X_Z^j and the free incoming electron. Taking into account the high mass ratio between the ion and the electron, the cross sections are actually functions of the absolute velocity (or energy) of the electron. Hence the ionization rates $C_{Z,j}(T)$ depend on the plasma temperature and are readily deduced by integration of the cross sections over the electron Maxwell-Boltzmann distribution. The number of X_Z^j ionization per

cm^3 and per sec is $n(X_Z^j)n_e C_{Z,j}(T)$ where $n(X_Z^j)$ and n_e are the ion and electron density.

An exact computation of the cross sections (or rates) is impossible. Indeed the ionization process is basically a N-body process with N≥3: it involves the ion core , a free electron and at least a bound electron. Hence cross section estimates relie on measurements or atomic physics approximations.

2 - CROSS SECTION AND RATE ESTIMATES

The semi-empirical formula of Lotz(1967), widely used in astrophysics, was developed at a time when the measurements were scarce. But now 42 ionization cross sections obtained with the crossed beam method are available for ions of astrophysical interest (mainly low charge ions). That method, which appears as the most reliable, directly provides the cross sections versus the energy of the incoming electron.

Some other astrophysicist favorite rates are those obtained by Summers (1974) who developped the first theoretical calculations for direct ionization using Exchange-Classical-Impact Parameter approximation (ECIP). We emphasize that these rates are about twice lower than those of Lotz. But now the theoretical context too has changed. For instance Younger (1980-1983) performed calculations in the Distorded Wave with Exchange approximation for 9 complete isoelectronic sequence and some Fe ions. The method he used is the most sophisticated available today. It is expected to be more and more accurate as Z increases in a given isoelectronic sequence. Besides a lot of cross sections were recently computed for the excitation autoionization process, of which crossed-beam experiments had already given evidence for some ions (see figure 1)

In view of these recent improvements we thought an updating of ionization rates was really needed (Arnaud and Rothenflug (1985)). Our approach differs significantly from the one adopted by Burgess and Chidichimo (1983) who recently proposed a modified Lotz formula based on 20 crossed beam measurements. Our work is based on both experimental data and theoretical works (that should not be ignored) and give separate estimates for the direct and autoionization rates. We proceeded as follows:

- For the direct ionization (D-I) cross sections we chose the formula proposed by Younger from its theoretical work (that formula, readily integrable allows to obtain the rates directly):

$$Q_{DI}(E) = \Sigma_j \frac{1}{uI_j^2} \{ A_j(1-\frac{1}{u})+B_j(1-\frac{1}{u})^2+C_j Ln(u)+D_j Ln(u)/u \} \qquad (1)$$

$u = \frac{E}{I_j}$ E beeing the incoming electron energy

A,B,D are free parameters (C is the Bethe coefficient calculated from photoionization cross section). The summation is performed over the subshells j of the initial ion. I_j is the ionization potential for the level j.

- When crossed beam measurements exist , the free parameter are adjusted in order to reproduce them correctly. Formula (1) ensures a very good fit of the measurements as long as D-I is the sole ionization process. For some isoelectronic sequences excitation-autoionization (E-A) is important. In that case a good fit is obtained with formula (1) below E-A onset. Extrapolation above that threshold is then reliable and provides the D-I process contribution. Hence subtracting it to the measurement allows to determine properly the E-A contribution. Easy to use formulae for E-A are provided in our paper. Figure 1 shows an example of our fit (ArV).

- We systematically compare measurements and theoretical results in every isoelectronic sequence (D-I and E-A processes are separatly discussed). For a given isoelectronic sequence most of the experimental works deal with low charge ions, whereas theoretical calculations appeared to be more and more accurate as the charge increases. Besides we noticed that theoretical and experimental estimates (when both are avaliable) are never in great conflict. Therefore we think we got reliable intrepolations and extrapolations where no measurement data exists. For details on the methods and dicussions see part II of our paper.

3 - CONCLUSION

We present a new evaluation of the ionization for astrophysically abundant elements, namely: H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, Ni. The computation code of ionization (and recombination) rates is available on request. When feeded with the appropriate parameters (temperature, atomic number and charge of the ion) that programme compute ionization (direct and excitation) and recombination (radiative and dielectronic) rates of any given ion.

It is worthwile to compare the present rates with the ones most often used in astrophysics (Lotz(1967) and Summers(1974)). It is clear from figure 2 that Lotz slightly over-estimates the direct ionization rates and gives good estimates <u>when</u> the E-A process is <u>not very</u> important. Summers systematically under estimates the rates for $j \geq 2$. Besides we emphasize the importance of taking into account the excitation autoionization process, specially for high Z ions in the Li, Na, Mg, Si sequences.

REFERENCES

Arnaud, M, Rothenflug, R, Astr.Astrophys.Suppl.Ser., 60, 425 and references therein
Burgess, A, Chidichimo M.C., 1983, M.N.R.A.S., 203, 1269
Lotz, W, 1967, Astrophys.J.Suppl., 14, 207
Summers, H.P., 1974, Appleton laboratory report, AL-R-5
Summers, H.P., 1974, M.N.R.A.S, 169, 663

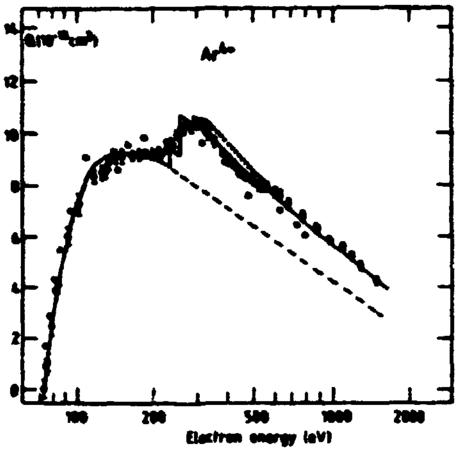

FIGURE 1 — Ionization cross section for Ar^{6+} (data points : filled circles with error bars from Crandall *et al.*, 1979) ; empty circles from Muller *et al.*, 1970). Full curve : total cross section, including the E-A contribution computed with the method that Sampson (198[illegible]) applied for the Na-like sequence. Dashed curve : D-I contribution. Dotted line : total cross section with our approximation to the E-A contribution (see text, Sect. 2.2.7.d).

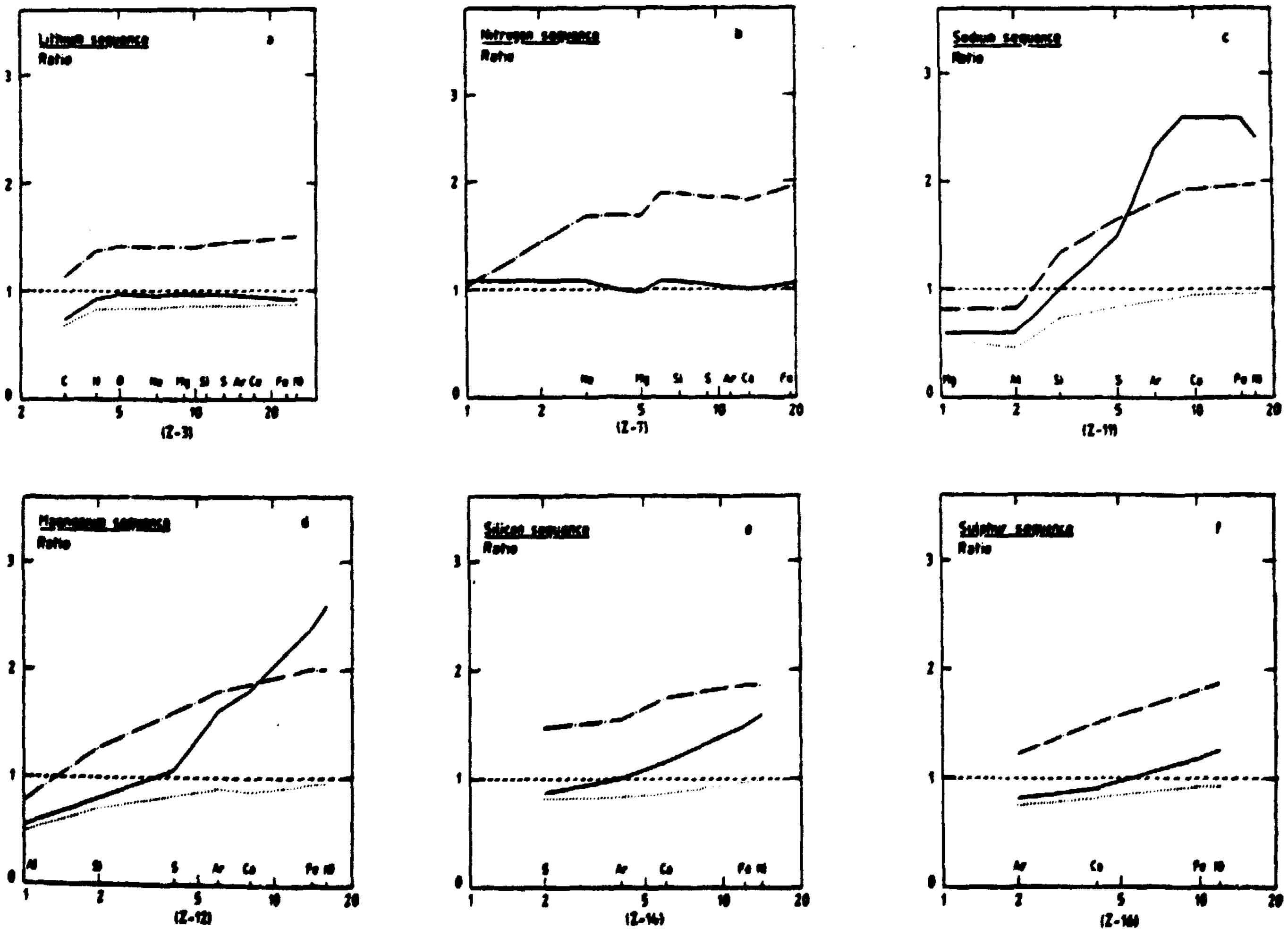

FIGURE 2 — Comparison of the ionization rates obtained in the present work with the Lotz rates and the Summer rates. Ordinates, the ratios of the following rates. Dotted curves : present work direct ionization over Lotz's rate. Full curves : present work total ionization rate *versus* Lotz's rate. Dot dashed curve : present work direct ionization rate *versus* Summer's rate. In the nitrogen sequence, there is no E-A contribution : the full curve represents the ratio of the present work direct rate to the Lotz rate. These ratios were calculated at the following temperatures : Nitrogen sequence : $kT = I_{2p}$ where I_{2p} is the outer shell ionization potential. Other sequences : $kT = I_{EA}$ where I_{EA} is the E-A onset.