THE EXCITATION EQUILIBRIUM OF CORONAL IONS

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Abstract. The relative populations of levels of highly ionized Fe, Ni and Ca ions have been calculated for physical conditions appropriate to the solar corona. The results are presented in the form of tables. Line intensity ratios in the EUV and visible that are sensitive to electron density are discussed and compared with observations.

1. Introduction

Much of our present understanding of the physical conditions in the solar corona is derived from the analysis of its line spectrum. The very existence of these lines immediately suggests a high-temperature, low density gas. In recent years the line spectrum has yielded detailed information on the temperature structure, chemical composition and spatial distribution of the corona over active regions.

This paper presents new calculations of the excitation equilibrium of Fe, Ni and Ca under coronal conditions. Such calculations are basic to any detailed analysis of spectroscopic coronal observations both in the EUV and in the visible.

The present work was motivated by three parallel developments. Firstly, a series of solar eclipse expeditions (Jefferies et al., 1968) have yielded excellent new observations of the coronal forbidden line spectrum. Absolute intensities have been obtained for 42 lines; 26 of these have been identified. The data is especially complete for three elements. Iron ions from Fe^x to Fe^{xv} are each represented by at least one line; Ni is present at Ni^{xii} through xvi except for Ni^{xv}, and three ions of Ca are visible: xii, xiii and xv. I have concentrated on these ions in this paper.

Secondly, the permitted line spectrum of these same ions, and to some extent their spatial distribution over the solar disk, has been observed repeatedly from rockets (Hall et al., 1965; Austin et al., 1966) and satellites (Neupert, 1967; Withbroe, 1969). Finally, new atomic and spectroscopic data have become available for highly ionized elements of astrophysical interest, chiefly through the efforts of the experimental group at Culham (Fawcett et al., 1967, 1968) and of the theoretical group of Krueger and Czyzak (1965, 1966, 1967). Although the availability of cross-sections and transition probabilities is constantly and rapidly improving, the time seemed ripe for a recalculation of the excitation equilibria.

In the following sections, I summarize the atomic data and the expressions used for the rate coefficients. Appendix 2, which contains the equilibrium populations of the radiating levels as functions of temperature and electron density, is discussed in the
final section. The application of these results to the analysis of the coronal forbidden line spectrum is reserved for a second paper.

2. Atomic Data

In this paper I am concerned with the excitation equilibrium of Fe, Ni and Ca ions having ground configurations of $3s^2$, $3s^23p^n$, or $2s^22p^n$ ($n=1,2,4,5$), under physical conditions appropriate to the solar corona.

The strongest permitted lines of coronal Fe and Ni observed in the EUV belong to transitions between the ground configuration ($3s^23p^n$) and the lowest excited configurations ($3s^23p^{n-1}3d$ and $3s3p^{n+1}$). Almost all the identified forbidden lines in the visible arise from transitions among levels in the ground configuration. In order to interpret all the observations for a given ion, it would be necessary to include all the terms of at least the ground and two excited configurations; in addition, terms from $4s$ and $4d$ should also be included, since cascades from these terms may influence the populations of lower terms.

However the number of predicted levels (Moore, 1949) becomes quite large (66 for Fe $\text{xiii}$, for example) and many of the important atomic parameters are unknown. As a reasonable compromise, I limited the number of levels to those shown in Appendix 1a. In choosing these levels I was guided partly by the availability of theoretical transition probabilities for the $3s^23p^n$-$3s^23p^{n-1}$ transition arrays (Fawcett et al., 1968) and $3s^23p^n$-$3s3p^{n+1}$ arrays (House, 1967). Nevertheless, it was necessary to estimate (or guess) a considerable number of transition probabilities, as the discussion below will show.

Preliminary calculations, in which high-lying levels were omitted, suggest that a sufficient number of levels has been included to give reliable populations for the ground-state levels. The populations of the higher levels become progressively less reliable, partly because of the neglect of cascades from $4s$ and $4d$ terms and partly because the rates of intersystem transitions (e.g. $1D-3P$) are largely unknown.

The populations of the levels of a given ion are determined, for a fixed temperature and electron density, by the steady-state equations

$$n_i \sum_{j \neq i} (A_{ij} + C_{ij}) = \sum_{k \neq i} n_k (A_{ki} + C_{ki})$$

which express the balance of the rates of population and depopulation for each level. The radiative and collisional rates ($A_{ij}$ and $C_{ij}$, respectively) involve such atomic parameters as oscillator strengths, collision strengths, and excitation potentials, which are set out in Appendix 1. The columns in the tables in Appendix 1a contain the following: (1) level number, (2) configurations, (3) excitation potential, in volts; Appendix 1b contains matrices of permitted absorption oscillator strengths, $f_{ij}$; while Appendix 1c summarizes transition probabilities, $A_{ij}$, and collision strengths, $\Omega$, for forbidden transitions. Sources for E.P., $f$, $A$, and $\Omega$ are numbered at the end of the Appendix and indicated within parentheses at the bottom of the column.

I discuss the sources of these atomic data below.