Mem. S.A.It. Vol. 74, 643

Memorie della

Non-Equilibrium Ionization Effects Induced During Coronal Flares

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Abstract. We present preliminary results of hydrodynamic modeling of flares occurring in plasma confined in coronal loops. Our analysis focuses on the deviations from ionization equilibrium on the population fractions of the most abundant elements in astrophysical plasmas, and on the possible implications for plasma diagnostics.

Key words. Hydrodynamics – Numerical Codes

1. Introduction

The solar corona is well known to be a rather dynamic environment and non-equilibrium ionization (NEI) effects may be produced by a variety of processes, including plasma flows through steep temperature gradients or sudden variations of temperature. On the other hand, the analysis of UV and X-rays observations (e.g. spectral lines) is a powerful diagnostic tool of the physical conditions in astrophysical plasmas. Since any deviation from equilibrium may have a non-negligible effect on the UV and X-rays emitted spectrum, it is crucial to take into account this effect on the analysis and interpretation of the observations.

In this paper we report on the preliminary results obtained from the analysis of the NEI effects induced during a compact flare confined in a solar coronal loop. The correct analysis of these effects may be important for an accurate simulation of emitted spectra and thus for diagnostics.

In this project, we use the FLASH code, an accurate numerical code for parallel computers capable of handling general compressible flow problems in astrophysical environments. Our group is collaborating with the Center for Astrophysical Thermonuclear Flashes (FLASH center), at the University of Chicago, to upgrade, to test, and to apply extensively FLASH. A key task of our group is the development of new numerical modules extending the field of applicability of FLASH to other fields of astrophysics, such as solar and stellar coronae. An essential ingredient is the intro-

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duction of the treatment of non-equilibrium ionization processes.

2. Hydrodynamic modeling and NEI

We model a coronal magnetic flux tube as a semicircular loop of semilength L and cross-sectional area uniform along the loop. The coronal loop contains low β plasma, and we assume that cross-field fluid motions and thermal conduction are negligible so that a one-dimensional description is adequate. The model takes into account the gravity stratification, the thermal conduction, the plasma viscosity[1], the radiative losses, the heating (via a phenomenological term), and the NEI effects. The fluid equations of mass, momentum, and energy conservation are in the form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \rho \mathbf{v}\mathbf{v} + \nabla P = \rho \mathbf{g} + \nabla \cdot (\nu \nabla \mathbf{v})$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\mathbf{v} = \rho \mathbf{v} \cdot \mathbf{g}$$
$$+ \nabla \cdot (\kappa \nabla T) + Q(s,t) - n_e n_H \Lambda(T)$$

$$\frac{\partial n_i^Z}{\partial t} + \nabla \cdot n_i^Z \mathbf{v} = R_i^Z \qquad \begin{matrix} (Z = 1, ..., N_{elem}) \\ (i = 1, ..., N_{ion}^Z) \end{matrix}$$

where $\quad E = \epsilon + 1/2\ |\mathbf{v}|^2$

is the total plasma energy (internal energy ϵ plus kinetic) per unit mass, ρ is the plasma mass density, $\mathbf{v}$ the plasma flow speed, t the time, $P = (\gamma - 1)\rho\epsilon$ the pressure, g the component of gravity parallel to the field lines, $\nu = 1.25 \times 10^{-16} T^{5/2}$ the coefficient of plasma compressional viscosity (Spitzer 1962), T the temperature, $\kappa(T) 9.2 \times 10^{-7} T^{5/2}$ the thermal conductivity in c.g.s units (Spitzer 1962), $Q(s,t)$ the phenomenological heating rate, n_e and n_H are the electron and hydrogen number density respectively, $\Lambda(T)$ is the radiative losses per unit emission measure (Raymond and Smith 1977), $\gamma = 5/3$ the ratio of specific heats, n_i^Z is the number density of the ion i of the element Z, N_{elem} is the number of elements, N_{ion}^Z the number of ionization states of element Z, and

$$R_i^Z = n_e [n_{i+1}^Z \alpha_{i+1}^Z + n_{i-1}^Z S_{i-1}^Z - n_i^Z (\alpha_i^Z + S_i^Z)]$$

where α_i^Z are the collisional and dielectronic recombination coefficients, and S_i^Z the collisional ionization coefficients (Summers 1974). The phenomenological heating is prescribed as a constant and uniform component plus a transient component deposited on the top of the loop (Peres et al. 1987):

$$Q(s,t) = E_H + H_0 \times g(s) \times f(t)$$

where E_H is the intensity of the constant and uniform component, H_0 the peak value of the transient component, $g(s)$ and $f(t)$ are the distribution along the loop coordinate s and time dependence of the transient heating defined as

$$g(s) = \exp[-(s - s_0)^2 / 2\sigma^2]\ ,$$

$$f(t) = \begin{cases} 0, & t \le t^* \\ 1, & t^* < t \le t_0 \\ \exp[(t_0 - t)/\tau], & t > t_0 \end{cases}$$

where s_0, σ, t^*, t_0, and τ are the parameters characterizing the spatial and temporal dependence of the impulsive heating.

3. Results

We model a compact flare observed with Solar Maximum Mission (SMM) on November 12, 1980 and studied in detail by MacNeice et al. (1985), and Peres et al. (1987). The flare evolution is well known

[1] Note that, in the current version of the FLASH code, the fluid equation of energy does not take into account the viscosity term, as its effect is assumed to be small. The results presented here, therefore, have to be considered preliminary.

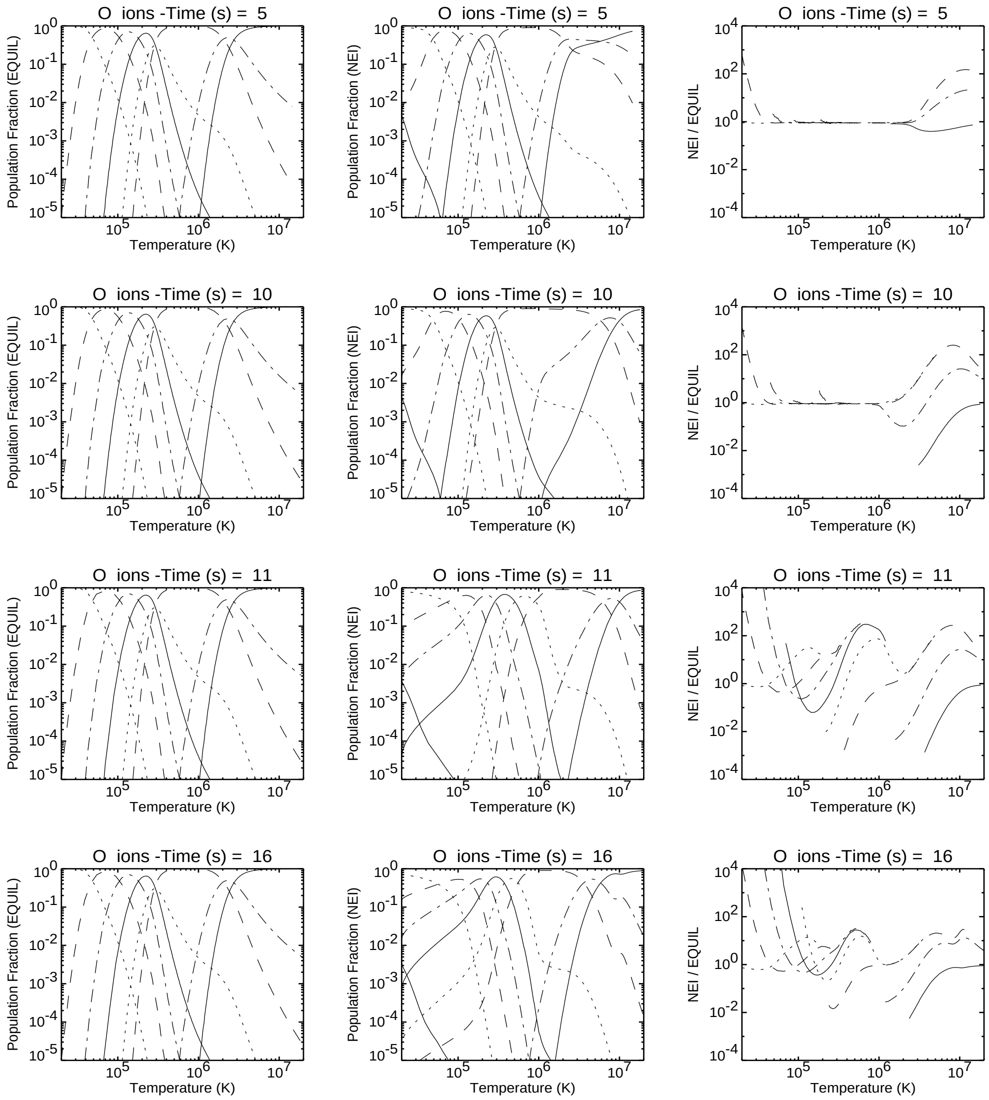

Fig. 1. Population fraction of Oxygen, n_i^O, vs. temperature along the loop. Panels from top to bottom are for increasing time (in seconds). Left panels show n_i^O assuming ionization equilibrium (EQUIL), central panels those in non-equilibrium of ionization (NEI), and the right panels the ratio of them (NEI/EQUIL). Each line corresponds to a different population fraction.

from these previous works and we focus only on the NEI effects. We adopt the boundary and initial conditions as well as the parameters characterizing the volumetric heating according to those adopted by Peres et al. (1987): we model a loop with semilength $L = 2.5 \times 10^9$ cm and with maximum temperature $T = 3.2 \times 10^6$ K and plasma pressure at the base of the transition region $P_0 = 6$ dyn cm^{-2} in the pre-flare conditions. The transient heating is located at the top of the loop ($s_0 = 2.5 \times 10^9$ cm, $\sigma = 5 \times 10^8$ cm) and is characterized by: $H_0 = 10$ erg cm^{-3} s^{-1}, $t^* = 0$, $t_0 = 180$ s, and $\tau = 60$ s; the uniform heating is defined by $E_H = 1.25 \times 10^{-2}$ erg cm^{-3} s^{-1}.

In the flare evolution, we can identify two main phases (see Peres et al. 1987; Peres & Reale 1993). In the first one (within the first 10 s since t^*) the impulsive heating determines a rapid increase of the plasma temperature in corona to typical flare values ($T \sim 10^7$ K). The pressure increases in corona pushes plasma downwards and produces a downward motions. Simultaneously, a conduction front propagates downward to the chromosphere. In the second phase (after approximately 10 s since t^*) the conduction front reaches the chromosphere and starts to heat it. As a consequence, the chromospheric layers rapidly expand upward determining a chromospheric evaporation.

In both phases of the flare evolution we expect NEI effects: in the first one due to the sudden temperature increase in corona, and in the second phase due to the violent flows carrying the cold plasma of the chromosphere through the transition region in the hot corona. As an example, in Fig. 1, we show the population fractions of Oxygen derived assuming ionization equilibrium, those in non-equilibrium of ionization and the ratio between the two, sampled at significant times. The figure shows that during the first phase of the flare evolution ($t \leq 10$ s), significant NEI effects are present in corona ($T > 10^6$ K) due to the temperature increase caused by the impulsive heating. During the second phase ($t > 10$ s) strong NEI effects are evident in the whole loop due to the rapid upward expansion of the upper chromospheric layers through the steep temperature gradient of the transition region (chromospheric evaporation), causing the presence of under-ionized plasma in corona.

4. Summary and Conclusion

In this paper, we discuss the preliminary results obtained from the modeling of NEI effects induced during the evolution of a compact flare. We find significant NEI effects during the first minute of the evolution due both to local variations of temperature and large plasma flows through the transition region (chromospheric evaporation). We expect, therefore, that the emission in spectral UV and X-ray lines and bands may be strongly affected by non-equilibrium ionization during a flare, and the interpretation of UV and X-ray data should take into account the NEI effects.

In the next future, we plan to study systematically the time-dependent NEI effects induced by dynamic phenomena in corona through the simulation of flares characterized by different physical parameters. The comparison of the modeling results with relevant observations will provide a powerful diagnostics of the physical conditions in the solar corona.

Acknowledgements. This work was supported in part by Agenzia Spaziale Italiana and by Ministero della Università e della Ricerca Scientifica e Tecnologica.

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