Publ. Astron. Obs. Belgrade No. 60 (1998), 39 – 42 *Contributed paper*

X-RAY EMISSION IN SOLAR FLARES

A. C. DONEA and G. MARIŞ
Astronomical Institute of the Romanian Academy,
Cuţitul de Argint 5, RO-75212, Bucharest, Romania
E–mail adonea@roastro.astro.ro

Abstract. Understanding the mechanisms of the X-ray production in solar flares sheds new light on the X-ray emissions in stellar flares, and other kind of explosion events observed in accretion disks, novae and supernovae remnants. The acceleration mechanism of electrons and ions is the key point in understanding the flare process. Since the X-ray fluxes are direct signatures of the acceleration and heating processes which occur during the energetic events (the flares), details about the non-thermal electron distribution can be inferred.

1. INTRODUCTION

Recent high resolution spectra of the solar flare events reveal new aspects on the physics inside the Sun. A number of solar X-ray satellites, such as *SMM, Hinotori, Yohkoh, ASCA, Einstein* and many other have provided many spectroscopic data which have allowed much progress in the understanding of the solar corona.

The X-ray spectra are signatures of the existing of different populations of the electrons inside the plasma of the solar flares. It remains to look at every observed X-ray flux from the solar flares to find out the type of the electron (thermal or non-thermal) accounting for the soft and hard X-ray observed structures. Observations of X-rays allows us to study the plasma temperatures and the densities of the accelerated particles.

The X-ray spectra of the solar flares have continuum components over which a forest of emission lines overlap. Studies of the emission lines intensities and profiles can provide information on temperature, density, abundances, plasma flows and non-equilibrium conditions.

Energetic solar flares have three stages. In the first stage (of a few minutes) the soft X-ray flux increases above the background solar X-ray flux. In the second stage bursts of hard X-ray and gamma-ray appears (lasting few seconds). In the third stage hard X-ray and gamma-ray intensities taper off exponentially. During the last two stages, the soft X-ray intensity is growing, until later, it will return to the normal stage.

The three stages show that the electron population inside the hot plasma, during the flare evolution, is changing. From the X-ray spectra one can distinguish the radiation emitted by hot, thermal electrons (with Maxwellian distribution functions) from that emitted by the accelerated, nonthermal electrons (power-law distribution functions). Comparing the hard X-ray and soft X-ray fluxes, taken at different stages in the evolution of a solar flares, one can find details of the evolution in time of the electron distribution. The soft X-ray photons are bremsstrahlung photons emitted by thermal electrons of temperatures of several million degrees K. The hard X-ray spectrum is dominated by bremsstrahlung from the accelerated electrons with power law energy distribution.

2. NON-MAXWELLIAN ELECTRONS AND THE X-RAY EMISSION

Finding the electron distribution of the electrons and ions during the solar flares requires the understanding of the acceleration mechanism in solar flares, which in fact is not yet fully understood. From the radio fluxes one can deduce the number and the energy distribution of the highly accelerated electrons during the flares.

On the other hand, the solar corona is orders of magnitude hotter than the underlying chromosphere. Scudder (1992) has argued that the high coronal temperatures can be explained in terms of the non-thermal non-Maxwellian particle distribution at the coronal base. The obtaining of the non-Maxwellian electron distribution in the corona is a matter of the acceleration mechanisms, too.

The non-Maxwellian electrons fill the gap in phase space, between the thermal Maxwellian electrons and the solar cosmic ray electrons. The thermal pool is provided by the immense mass of the hot solar corona. Having an efficient injection mechanism the nonthermal population of the electrons has to bridge between the thermal and solar cosmic ray electrons.

An explanation of the X-ray emission as bremsstrahlung from the nonthermal electrons has been proposed by Donea & Biermann (1998) for the case of X-ray fluxes of the supernovae remnants. Since the acceleration of the electrons involves the shock acceleration processes and the magnetic field structure of the environment, a similar mechanism can accelerate electrons from the thermal pool in the hot flare plasma. The thermal electrons gain energies through the drift mechanism inside the thickness of the shock.

The X-ray emission spectra of hot, optically thin plasma were calculated by Kato (1976), Mewe (1972), Raymond and Smith (1977) for a range of plasma temperatures. Their work provides a complete reference for explaining the X-ray fluxes in supernova remnants and solar corona. A Maxwell distribution of electron velocities was assumed.

However, the solar flares and several supernova remnants show power-law spectra in the X-ray domain and this is the evidence of nonthermal emission from the shocked shells.

We have computed the photon generation using the bremsstrahlung cross sections reviewed by Blumenthal and Gould (1970). The differential cross sections for electrons that have supra-thermal energies have been kindly provided by A.W. Strong (Strong 1994). At high frequencies the bremsstrahlung production is dominated by the cosmic ray electrons.

A supra-thermal population of electrons introduces new elements in the analysis of the X-ray emission from the shocked plasma. The ionization state of the shocked plasma is different than the case when a Maxwellian population do the excitation-recombination work.

The supra-thermal electrons at energies of several keV produce line excitation, because the cross section for an electron on a Si, Mg, S or Fe ion has the resonance, at approximately the energies of the supra-thermal electrons (the collisional excitation by electrons varies as v_e^{-2} above the threshold, Osterbrock (1968)). Therefore, one expects even higher emission lines in the X-ray spectra from the hot plasma.

We analyze the ionization-recombination balance for the case of the Si^{+12} He-like line, which appears in the X-ray spectrum at the energy of 1.865 keV.

3. THE IONIZATION RATES BY ELECTRONIC COLLISIONS

For direct ionization cross sections we used the formula given by Arnaud and Rothenflug (1985). The ionization potential for a certain level is taken from Lotz (1967). One integrates over a power law velocity distribution of supra- thermal electrons. The coefficients of the ionization are computed for different injection energies of the supra-thermal electrons (see Figure 1.).

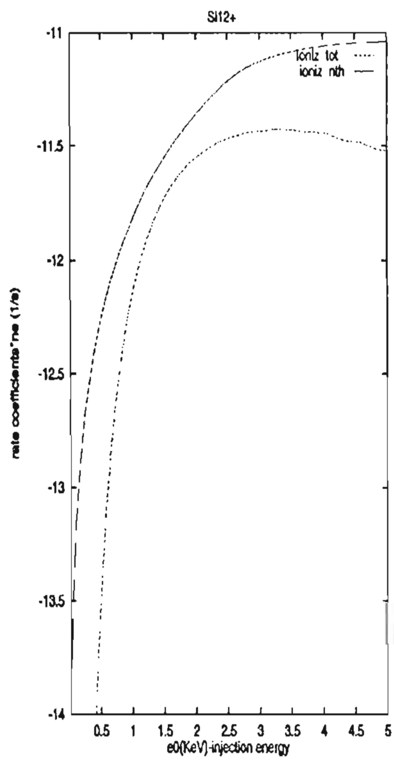

Fig. 1. The ionization rates (1/s) of Si^{+12} for a supra-thermal population of electrons starting at different injection energies. The ionization recombination rates (1/s) for Maxwellian electrons, having various temperatures T, is shown with the dashed line. For comparison to the supra-thermal case we made the analysis with respect to the ε_0 which is equal to $k_B T$. k_B is the Boltzmann's constant and ε_0 is the injection energy of the supra-thermal electrons. $T = 10^7$ K means $\varepsilon_0 = 0.87$ keV. The ionization coefficients are multiplied with an electron density $n_e = 0.1(1/\text{cm}^3)$. The n_e in solar flares is $10^8(1/\text{cm}^3)$.

We compare the ionization rates for two cases: a) when the plasma contains thermal electrons of temperature T and b) when these are replaced by transitional-thermal electrons and supra-thermal electrons. We assumed that only the ground level is significantly populated and we ignore all the other levels. The ionization rates corresponding to the ground level of Si^{+12} ion are shown in the Figure, for supra-thermal and thermal population of electrons, respectively. The supra-thermal electrons ionize faster than the thermal electrons, therefore the number of Si^{+12} ions in plasma is reduced. For an injection energy of 0.86 keV ($T = 10^7$K) the ionization rate is approximately half an order of magnitude higher than the Maxwellian case. It is likely that in some cases the ionization process is not fast enough for reducing the number of Si^{+12} ions.

4. CONCLUSION

Using the result from the previous section we stress the fact that the supra-thermal electrons can modify the ionization balance in the hot shell. Therefore, the emission lines will have different intensities compared to the equilibrium case when a thermal population of electrons is taken into account. We conclude that from the X-ray spectra of the solar flares one can find details about the nonthermal electrons distributions and the injection mechanisms. The nonthermal electrons produce power-law bremsstrahlung photons with hard X-ray energies and also contributes to the ionization state of the hot plasma.

The solar flares are the closest laboratories for searching the the three existing population of electrons: thermal, supra-thermal and relativistic.

References

Arnaud, M., Rothenflug, R.: 1985, *Astron. Astrophys. Supp.*, **60**, 425.
Blumenthal, G.R., Gould, R.J.: 1970, *Rev. Mod. Phys.*, **42**, 237.
Donea, A.C., Biermann, P.L.: 1998, *Astron. Astrophys.*, submitted.
Kato, T.: 1976, *Astrophys. J. Supp.*, **30**, 397.
Lotz, W.: 1967, *Astrophys. J. Supp.*, **14**, 207.
Mewe, R.: 1972, *Solar Phys.*, **22**, 429.
Osterbrock, D.E.: 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, Mill Valley, California.
Raymond, J.C., Smith, B.W.: 1977, *Astrophys. J. Supp*, **35**, 419.
Scudder, J.: 1992, *Astrophys. J.*, **398**, 299.
Strong, A.W. *et al.*: 1994, *Astrophys. J. Supp.*, **92**, 425.