THE EMISSION MEASURE AND ULTRAVIOLET SPECTRA OF T TAURI STARS

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ABSTRACT - We present the characteristics of the ultraviolet spectra of T Tauri stars and summarise the relevance of ultraviolet Astronomy and its historical development. The emission measure is discussed and related to the quantification of the material responsible for the observed ultraviolet emission. We compare the ultraviolet data for three T Tauri stars (RU Lupi, T Tauri , GW Orionis) and the Sun and show that the energy emitted by these stars in the temperatue range 10^4-5.10^4 K is typically 10^3 times higher than the corresponding solar values. This suggests that the "young" Sun, when only a few 10^6 years old and still evolving to the main sequence, must have had a much higher ultraviolet flux than at the present time.

1 - INTRODUCTION

1.1 - THE ULTRAVIOLET OBSERVATIONS

Astronomical observations at ground level are limited to the narrow band of visible radiation, λ[3250,10000] Å, a few bands in the infrared (λ [2.0,4.4] μm , λ [8,13] μm , around 20 μm and 30 μm) and the radio bands (mm and cm). Therefore most of the electromagnetic spectra is completely inaccessible even from the best placed observatories.

While in the infrared band the situation can be improved using airborne telescopes, for example the Kuiper Airborne Observatory, this procedure is not possible for most bands, for instance, the absorption of ultraviolet radiation by the ozone layer in the earth's atmosphere requires ultraviolet observations to be made at a height above 100 Km.

Astronomical observations in the ultraviolet are very important since for the most abundant atoms and ions , the most relevant radiative transitions occur at ultraviolet wavelengths, namely in the region λ [1200,2000]Å. Actually, for atoms and ions of H, C(I,II,III,IV), Si(I,II,III,IV), MgII, etc, the energy differences between the first excited level and the ground level are 5 to 10 eV; therefore, electrons with a Maxwellian velocity distribution characteristic of temperatures between 10^4 and $2\,10^5$ K have sufficient energy to collisionally excite such atoms or ions that will subsequently produce strong spectral lines through radiative decay. These temperatures are typical of stellar atmospheres, galaxies, HII regions, planetary nebulae and other astrophysical objects that will naturally show a very rich ultraviolet spectrum. Furthermore, the absorption of the ultraviolet photons by the lower temperature materials located between the observer and the object, for example, the circumstellar and interstellar medium (in particular the local one, i. e., at a distance up to 100 parsec) or by intergalactic material will also produce spectral lines that will provide information on the properties of such material.

The development of ultraviolet Astronomy is quite recent and comprises essentially three distinct phases:

First phase - Balloons and rockets (*Aerobee*) transporting simple photometers were used in the second half of the 1950's.

Scanning measurements were made by means of rockets undergoing free movement in space [1],[2],[3]. The first ultraviolet spectrophotometric observations of stars [4] were made in the 1960's; the first spectrum with enough resolution to allow the detection of individual lines dates from 1965. This was obtained using similar rockets now stabilized in 3 axis thereby allowing longer exposures [5]. By the end of the decade photometric spectroscopic observations for some of the brighter stars were already available. Very short exposures (of the order of minutes) were achieved even though much longer exposures would be required.

Second phase - This phase took place during the 1970's. The measurements were made using sattelites within the framework of a programme for ultraviolet Astronomy called **O**rbiting **A**stronomical **O**bservatory (**NASA**). These satellites were equipped with low resolution spectrometers and cameras sensitive in the region λ[1200, 4000] Å. In 1972, the satellite **OAO-C** (also known as **Copernicus**) provided very high resolution observations ($\lambda/\Delta\lambda \approx 10^5$) for very bright stars, $V \leq 6$. That same year the first european ultraviolet satellite **TD-1**, carried out a complete spectrophotometric survey (wide band photometry 150-200 Å and a spectroscopic survey in the λ[2000, 3000] Å) for stars of magnitude $V < 11$, [6,7].

Third phase - This is the period in which space observatories started to be used. The **I**nternational **U**ltraviolet **E**xplorer was the first ultraviolet space observatory operated in real time, while the experiments just described were preprogrammed. The satellite **IUE** (**NASA**, **ESA** and **SERC**), launched in 1978, is equipped with a Ritchey-Chrétien telescope with a mirror of 45 cm, aperture F/15 and field of ≈16'. It also has two "echelle" spectrographs, one for short wavelengths, $\lambda[1150, 1950]$Å and another for long wavelengths, $\lambda[1900, 3200]$Å. Both operate in two resolution modes:

- low resolution (using only one order and limited to objects with $V \approx 17$) with $\lambda/\Delta\lambda \approx 300 \rightarrow \Delta\lambda \approx 6$ or 7 Å, and
- high resolution (about 50 orders, amplitude ≈ 20Å, 300 μm separation, used for objects of magnitude up to $V \approx 12$) with $\lambda/\Delta\lambda \approx 10^4 \rightarrow \Delta\lambda \approx 0.1$ to 0.3 Å.

The **IUE** detectors are video cameras that are preceded by ultraviolet to visual photon converters. The image, composed of 768x768 pixels is transmited to earth in real time after being digitised in 256 discrete levels of intensity. The data are then subjected to an elaborate sequence of operations including:

- photometric calibration for each pixel,
- correction for non-linearity of the detector at high intensity levels,
- wavelength calibration,
- weighing each element according to its quality,
- correction for the background noise,
- calibration in flux units of the system telescope/ spectrograph /detector.

In this way we obtain a calibrated spectrum ready for analysis.

1.2 - T TAURI STARS

T Tauri are recently formed stars, not older than a few 10^6 years and still evolving towards the main sequence. They are low mass stars, typically less than three solar masses and exhibit unusual spectra. This makes their study very interesting, because of their intrinsic properties and also from an evolutionary point of view. We aim at establishing a consistent image of stellar evolution, from the initial stages just after the contraction of dense molecular clouds to the arrival of the stars at the main sequence. There are still important problems of these initial phases of evolution to be understood, namely the role of magnetic fields, the reduction of angular momentum and the phenomena of mass accretion and stellar winds. Related to this problem is the formation of the sun and solar system. The ultraviolet observations of T Tauri stars will help the characterisation of conditions prevailing in their atmospheres and relevant to the establishement of models of stellar structure and evolution. They also provide a way to study the role of the ultraviolet radiation of the "young" Sun in determining the composition of the primitive earth's atmosphere and consequently the origin of the organic molecules that have preceded life on Earth ([8],[9]). We believe that T Tauri stars are precisely in such phase of evolution and that their study helps to understand the conditions that might have prevailed in the "young" Sun.

λ (Å)	*line*
1239-1243	NV(1)
1301-1306	OI(2), SiIII(4)
1335-1336	CII(1)
1394-1403	SiIV(1)
1548-1551	CIV(1)
1657	CI(2)
1697-1727	FeII(38)
1663	OIII
1808-1817	SiII(1)
1859	AlIII(1)
1892	SiIII(1)
1909	CIII(0.01)
2318-2350	CII,SiII
2600-2630	FeII(1)
2795-2803	MgII(1)
2930-2980	FeII(60)

Table 1-Major lines in the ultraviolet spectrum of T-Tauri stars.

1.3 - THE ULTRAVIOLET SPECTRA OF T TAURI STARS.

The ultraviolet spectrum of T Tauri stars is dominated by emission lines, mainly in the region λ<2000 Å. The continuum may also be intense for some stars but there are no absorption lines in that spectral region. For λ>2000 Å, the spectrum is generally more complex and includes a photospheric continuum as well as contributions due possibly to numerous lines of FeII.

The present study deals with only the emission line spectrum and its main characteristics can be summarised in the following way:

- the presence of numerous emission lines as shown on Fig.1. Table 1 gives the identification of the lines, the dominant lines being of OI, CII, SiII, CIII, SiIII, CIV, SiIV, FeII and MgII, although with a degree of intensity varying from star to star; the Mg II lines are generally very strong;
- Fig.1, shows that concerning the level of activity (as shown through the intensity of the observed emission lines) there is no simple correlation between the ultraviolet and the optical spectrum of a star.

From the ultraviolet observations it is possible to estimate the amount of material needed to produce the observed energy for each spectral line. This is the so-called emission measure.

2 - THE EMISSION MEASURE

2.1 - DESCRIPTION

The emission measure analysis was introduced by Pottasch [11] as a technique for the study of both the solar transition region and corona. The first studies combined this method with observations of spectral lines in the solar spectrum originated at similar temperatures; as a result, it was possible to evaluate the relative abundances of the various elements associated with those lines. Subsequently, it became clear that the values of the emission measure, together with the equation of hydrostatic equilibrium, were enough to specify uniquely the structure of the outer layers of the solar atmosphere. More recently, with information gathered by means of artificial satellites (Copernicus and **IUE**) such type of analysis was extended to other cool stars in which emission lines on the ultraviolet part of the spectrum (therefore characteristic of hot circumstellar regions) were observed.

The determination of the emission measure for a given spectral line requires knowledge of the corresponding energy flus at the surface of the star. In general, for a transition between the atomic levels j and i , this flux may be written as [12]

$$F^*_{ji} = \frac{hc}{\lambda}\frac{1}{4\pi R^2}\int_{\Delta V} N_j(\vec{r})A_{ji}P_{ji}(\vec{r})d^3\vec{r} \qquad (1)$$

where:

h is the Planck's constant,

c the speed of light,

λ the wavelength for the transition between levels j and i ,

R the radius of the star,

A_{ji} the probability of spontaneous decay,

$\vec{r}$ the positional vector with respect to the star,

$N_j(\vec{r})$ the density of atoms (or ions) in the state j, as a function of $\vec{r}$.

$P_{ji}(\vec{r})$ the probability for the photons to escape from the star, as a function of $\vec{r}$; it has the value 0.5 if we assume that only those photons emitted by the half side of the star facing the observer contribute to the flux.

Assuming that ΔV is the volume of a shell of material with spherical symmetry, between radius R and $R+\Delta R$, with $\Delta R \ll R$, and using as parameter the height h, measured from the bottom of the atmosphere, we get

$$F^*_{ji} = \frac{1}{2}\frac{hc}{\lambda}\int_{\Delta V} N_j(h)A_{ji}dh. \qquad (2)$$

N_j can be calculated from the equations of statistical equilibrium. Assuming that the atoms are kept in equilibrium through

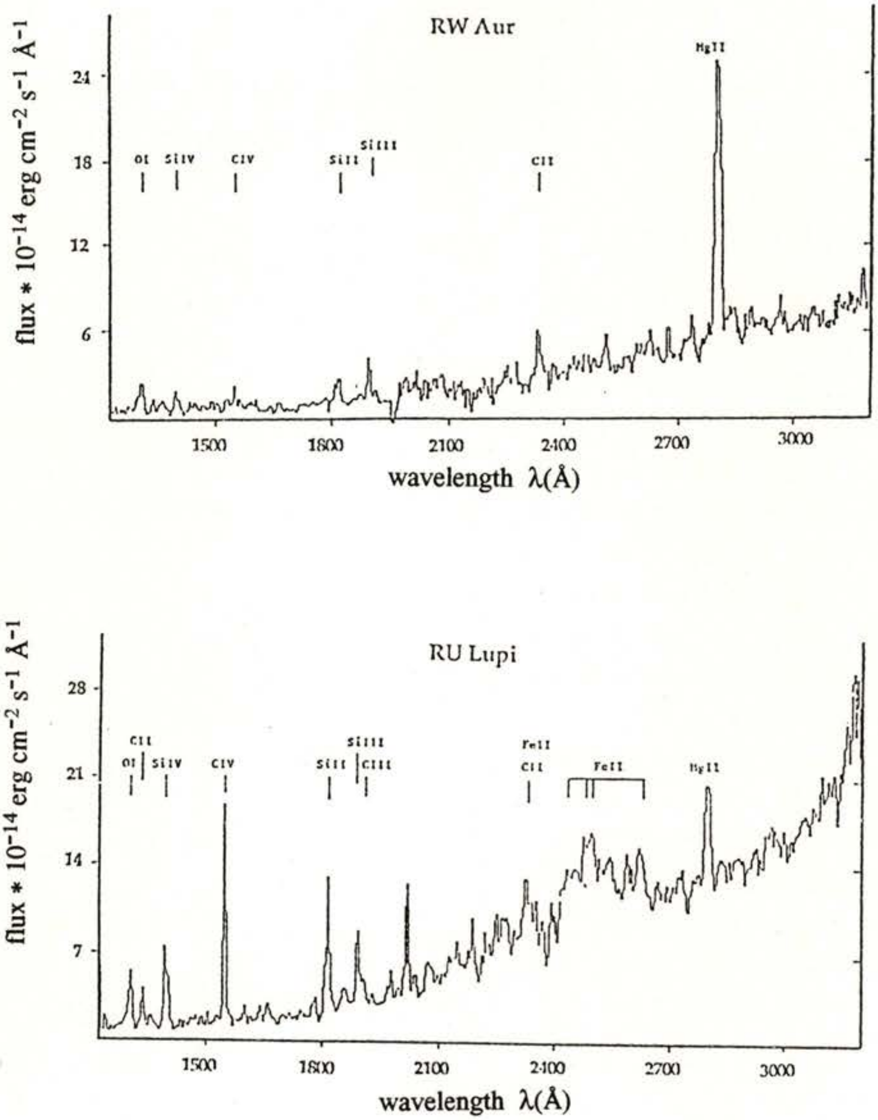

Fig. 1 - Ultraviolet spectrum for the stars RW Aur and RU Lupi. Although these two stars show very similar spectra in the visible region, the intensity of the different emission lines[10] of their ultraviolet counterparts are very different.

collisions and that each excitation by collision is followed by a radiative decay by which the electron returns to its initial stage, the equation of statistical equilibrium takes the simple form

$$N_j\, A_{ji} = N_i\, C_{ij} \qquad (3)$$

in which C_{ij} represents the collision rate for electrons on level i to "ascend" to level j. Usually such values are not known. Instead, we use the dimensionless quantity f_{ij}, the "oscillator strength", whose value depends on the intensity of the spectal line and the number of corresponding classical oscillators. The values C_{ij} can be obtained from the expression of Van Regemorter [13],

$$C_{ij}=1.7\ 10^{-3} N_e T_e^{-0.5} \chi^{-1} f_{ij} 10^{-(5040\chi/T_e)} P(\chi/k_B T_e) \qquad (4)$$

where:

k_B is the Boltzmann constant,

T_e the electronic temperature,

N_e the electronic density,

χ the excitation energy in eV,

$P(\chi/k_B T_e)$ the Gaunt factor (integrated in energy), usually identified by the letter *g*.

On the other hand, N_i can be expressed as

$$N_i = N_e \frac{N_H}{N_e} \frac{N_{el}}{N_H} \frac{N_i}{N_{el}} \qquad (5)$$

where:

N_H is the density of hydrogen,

N_{el} is the density of the element in all states of ionisation.

For the typical temperatures involved ($T \sim 10^5 K$), hydrogen and helium are almost completely ionised, and we can use the approximation

$$N_e \approx N_H + 2N_{He}. \qquad (6)$$

For a typical ratio $N_{He}/N_H = 1/10$, this gives

$$N_H = 0.8 N_e. \qquad (7)$$

Substituting equations (3), (4), (5) and (7) in equation (2), denoting by A the abundance of the element (N_{el}/N_H), and dropping the indexes ij, we get

$$F^* = 6.8\ 10^{-4} \frac{hc}{\lambda} \chi^{-1} A g f \int_{\Delta h} G(T_e) N_e^2 dh \qquad (8)$$

were

$$G(T_e) = T_e^{-0.5} 10^{-(5040\chi/T_e)} N_i/N_{el}. \qquad (9)$$

Pottasch [11] in his calculation, replaces the $G(T_e)$ within the integral by a mean value

$$\langle G(T_e)\rangle = 0.7\ G_{max}(T_m), \tag{10}$$

where $G_{max}(T_m)$ is the maximum value of $G(T_e)$. He then obtains

$$F^* = 2.97\ 10^{-15}\ Agf\ G_{max}(T_m) \int_{\Delta h} N_e^2 dh. \tag{11}$$

The term

$$\int_{\Delta h} N_e^2 dh$$

is called **emission measure (EM).** It represents the quantity of material needed to produce all the energy flux observed in the emission line, assuming that the line was formed at a single temperature T_m corresponding to the maximum of the function $G(T_e)$. A more refined procedure would need the determination of the normalisation factor (equal to 0.7 in this case) for each spectral line, through the numerical integration of $G(T_e)$ over a temperature range including T_m.

2.2 - ATOMIC PARAMETERS

Table 2 gives the atomic parameters for the lines of interest in the ultraviolet spectrum of T Tauri stars.

The value of gf for line 1 is given by [12]; all the others were calculated by means of the equation [15]

$$gf = \frac{6.28\ 10^{-7}}{\lambda}\frac{\Omega}{\omega} \tag{12}$$

using the values of the collision strength, Ω, and the statistical weight ω referred in [14]. In the case of ions with two energy levels in the fundamental state, we use an average value of gf given by

$$\langle gf\rangle = \frac{\omega_1 f_1 g_1 + \omega_2 f_2 g_2}{\omega_1 + \omega_2} \tag{13}$$

in which the indexes 1 and 2 identify the levels.

line	λ (Å)	gf	N_i/N_{el}	T_m
1. CII	1335.3	1.3	1.00	$4.0\ 10^4$
2. SiIV	1398	0.18	0.16	$7.4\ 10^4$
3. CIV	1550	0.23	0.25	$1.1\ 10^5$
4. SiII	1812	0.00237	0.91	$1.5\ 10^4$

Table 2-Atomic parameters for the relevant spectral lines.

The values used for the abundances of carbon and silicon were $3.2\ 10^{-4}$ and $6.3\ 10^{-5}$ respectively. The values of

N_i/N_{el} are listed in reference [13]; T_m for the spectrum line 4 is that of reference [13] and the values for all the other lines are given in reference [16].

T TAURI				
line	F_{obs} (erg cm $^{-2}$s^{-1})	F^*(erg cm $^{-2}$s^{-1})	$F^* /F_\odot$	EM (cm^{-5})
1. CII	$6.80\ 10^{-14}$	$4.34\ 10^{6}$	$6.57\ 10^{2}$	$1.04\ 10^{28}$
2. SiIV	$1.70\ 10^{-13}$	$8.91\ 10^{6}$	$2.47\ 10^{3}$	$1.76\ 10^{30}$
3. CIV	$4.60\ 10^{-13}$	$2.08\ 10^{7}$	$3.19\ 10^{3}$	$2.97\ 10^{29}$
4. SiII	$2.20\ 10^{-13}$	$8.58\ 10^{6}$	$3.62\ 10^{2}$	$5.18\ 10^{32}$

RU LUPI				
line	F_{obs} (erg cm $^{-2}$s^{-1})	F^*(erg cm $^{-2}$s^{-1})	$F^* /F_\odot$	EM (cm^{-5})
1. CII	$3.90\ 10^{-13}$	$2.76\ 10^{7}$	$4.18\ 10^{2}$	$6.59\ 10^{28}$
2. SiIV	$9.10\ 10^{-13}$	$5.91\ 10^{7}$	$1.64\ 10^{4}$	$1.17\ 10^{31}$
3. CIV	$1.50\ 10^{-12}$	$9.16\ 10^{7}$	$1.40\ 10^{4}$	$1.31\ 10^{30}$
4. SiII	$1.30\ 10^{-12}$	$7.44\ 10^{7}$	$3.14\ 10^{3}$	$4.49\ 10^{33}$

GW ORIONIS				
line	F_{obs} (erg cm $^{-2}$s^{-1})	F^*(erg cm $^{-2}$s^{-1})	$F^* /F_\odot$	EM (cm^{-5})
1. CII	$1.50\ 10^{-13}$	$9.20\ 10^{6}$	$1.39\ 10^{3}$	$2.20\ 10^{28}$
2. SiIV	$1.40\ 10^{-13}$	$7.68\ 10^{6}$	$2.13\ 10^{3}$	$1.52\ 10^{30}$
3. CIV	$2.20\ 10^{-13}$	$1.11\ 10^{7}$	$1.70\ 10^{3}$	$1.58\ 10^{29}$
4. SiII	$2.00\ 10^{-13}$	$9.27\ 10^{6}$	$3.91\ 10^{2}$	$5.60\ 10^{32}$

Table 3 - Fluxes and emission measures for some lines in the spectrum of the T Tauri, RU Lupi e GW Orionis stars.

2.3 - OBSERVATIONS

From observations in the ultraviolet we can deduce the observed flux, F_{obs}; correcting this value for the distance and interstellar absorption we can calculate the flux emitted by the star in each spectral line, F^*. This is done using

$$F^* = F_{obs}(\frac{d}{R})^2 10^{(0.4A_\lambda)} \qquad (14)$$

where

d is the distance of the star,

A_λ is the interstellar absorption in magnitude units .

The A_λ values are obtained from the interstellar extinction law defined by Savage e Mathis [17], through linear interpolation of the values $E(\lambda\text{-}V)/E(B\text{-}V)$

$$A_\lambda = A_V[1+\frac{1}{3.1}E(\lambda\text{-}V)/E(B\text{-}V)] \qquad (15)$$

Table 3 shows the data relative to the stars T Tauri, RU Lupi and GW Orionis. For the distances and radii we have used values extensively quoted in the literature, respectively 160 pc, 150 pc and 500 pc for the distances, $6R_\odot$, $1.8R_\odot$ and $8.4R_\odot$ for the radii.

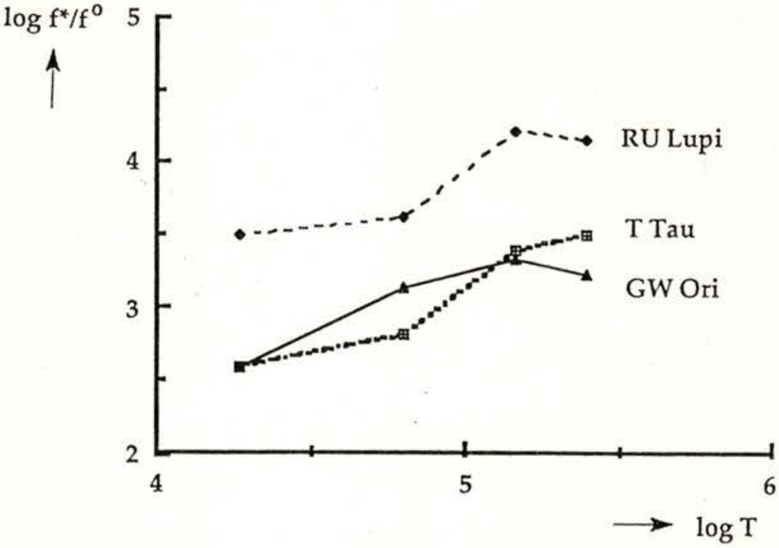

Fig. 2 - Distribution of the energy in the ultraviolet, for the three T Tauri stars. The corresponding emission of the sun is used as unity.

2.4 - CONCLUSIONS

Fig. 2 displays the distribution of the emitted energies corresponding to the spectral lines of the sun and of the three T Tauri stars, and summarises the results obtained through the present analysis. It clearly shows that in the T Tauri stars the energy flux (and consequently the material responsible for its production) coming from the regions with temperature in the interval $[10^4, 5\,10^4]$, is typically 10^3 times larger than that of the sun. In other words, the emission from this so called *transition region,* is highly enhanced in T Tauri stars. On the other hand, there are significant differences amongst the three T Tauri stars regarding not only the amount of energy flux (e.g. RU Lupi and T Tauri) but also its distribution (T Tauri and GW~Orionis). Since some of these stars are similar to, but much younger than the sun (in particular RU Lupi), the results suggest that during evolution towards the main sequence, just a few million years after its formation as a star, the sun might have been the source of a much higher ultraviolet flux than at the present time.

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