RECENTLY FORMED STARS: OBSERVATIONS AND MODELS (*)

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ABSTRACT — The impact of the recent observational achievements of Space Astronomy together with new developments in the theories of star formation, stellar evolution and the origin of the Solar System led to a burst in research work on recently formed stars.

This paper, a compilation of our own ongoing research in this topic is divided in three sections: 1 — The Introduction, where the properties characteristic of young stars, specially T Tauri stars, are summarized; section 2 — containing a brief description of our spectroscopic data (both in the UV and in the visual wavelength region) and of the resulting physical parameterization of the atmosphere of the star inferred from the analysis of these data, and section 3 — a brief reference to models we developed constrained by the observational results refered in the previous section.

Since the paper aims at a compilation more than a presentation of detailed work no effort has been made to explain, either techniques and methods used or how the results were obtained. References to those are occasionally given and we direct the interested reader to them.

1 – INTRODUCTION

While refering to young stars we will concentrate on the so called class of T Tauri stars. Without entering in the details of how a particular star will be classified as belonging to this class we will point out some of the peculiar characteristics of such class:

– T Tauri stars are low mass stars (1 to 3 solar mass),

– they exhibit a peculiar continuum energy distribution when compared to «normal» stars belonging to the same spectral class,

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i. e., as displayed on Fig. 1, their spectra show an excess emission all the way from the UV to the infrared wavelengths,

– although being cool stars (effective temperature in the range 3000 to 6000 K) they show an emission line spectrum overlapping the continuum. (The number and intensity of the emission lines present in the spectra varies from star to star; as a rule, there are always emission lines present to some degree),

– they are irregular variables.

Different lines of argument point to T Tauri stars as being young ($< 10^6$ years) stars still in the phase of gravitational contraction towards the main sequence [2]. These stars are located near dense molecular clouds to which they are observed to be dynamically associated [3]. These molecular clouds are known to be places of ongoing star formation.

For further reading we refer to a large number of recent articles on T Tauri stars scattered through the literature. Two review articles on T Tauri stars have also recently appeared; one [4], essentially dealing with the observations at different wavelengths, the other [5], describing theoretical modelling, although strongly biased towards the protostellar collapse phase. A more wide review of the T Tauri stars, including a critical analysis of models and mechanisms and their relations with the observations, however strongly needed, is yet to come.

2 – THE DATA

In this section we will present some of our spectroscopic data on T Tauri stars. We will concentrate on a particular T Tauri star, RU Lupi. For this star we have the most complete set of observations and the data analysis is at a more advanced stage.

2.1 – *The visual wavelength range*

Our data includes:

– several intermediate dispersion spectra (20 Å mm^{-1}) obtained at the Anglo-Australian Telescope. These spectra have been used for line identification and immediate analysis, such as the assessment of values of density and temperature for the

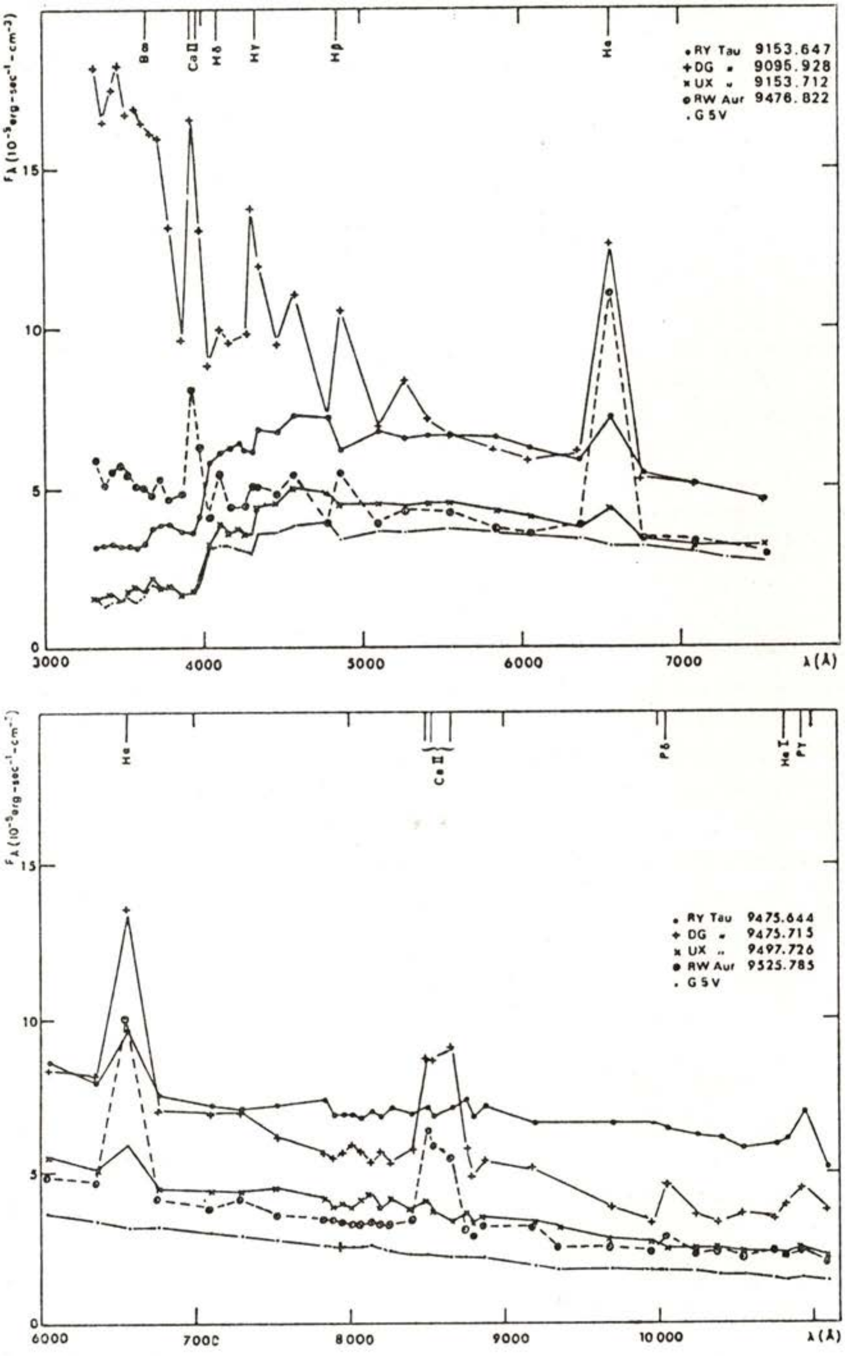

Fig. 1 — The spectral energy distribution of T Tauri stars classified as dG5. The lowest curve is for a standard G5V star (arbitrary vertical scale [1]).

different layers in the stellar atmosphere producing the emission lines [6]. The conclusions are compiled in Table 1 while Fig. 2 displays one of such spectra;

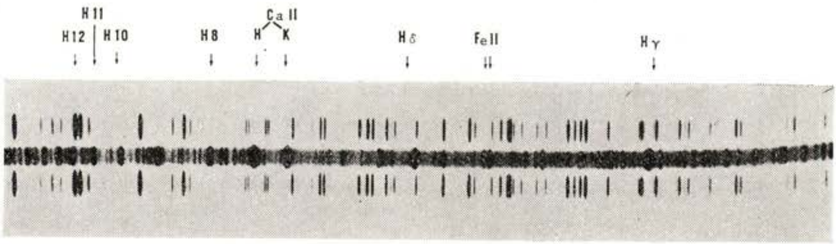

Fig. 2 — An intermediate dispersion spectrum of RU Lupi in the wavelength range [3600, 4580] Å. The spectrum was obtained with the Anglo-Australian Telescope and the Royal Greenwich Observatory spectrograph.

— high resolution spectra (at inverse dispersion 5 to 10 Å mm^{-1}) also obtained at the Anglo-Australian Telescope. This high quality data allows, through the detailed line profile analysis to conclude on the presence of suprathermal motions in the stellar atmosphere (from the line widths) and even of a strong stellar wind (from the line profile shape) [6]; furthermore we were able to get a velocity distance relationship (from the profile assymetry) [7]. These results are also included in Table 1a (the last line).

TABLE 1a — Summary of observational constraints of the wind of RU Lupi suggested by the optical data analysis.

	Fe I, Ti II	Fe II	Ca II, H I	He I
density (cm^{-3})	$N_p < 10^{12}$ $N_H = 10^{14}$ $N_e < 10^{12}$	$N_e > 10^9$		$N_e > 10^{11}$
temperature (K)	5800		10^4	10^5
velocity (Km s^{-1})	170		240	

2.2 — *The ultraviolet data*

Over the last five years a wealth of information on every field in Astronomy has resulted from the activity of the International Ultraviolet Explorer (NASA-ESA). T Tauri stars are no exception and a large amount of data on such stars is now available in the data bank. Our own observations include:

— low resolution spectra (Fig. 3) that has led to conclude on the presence in the T Tauri stars of a transition region, similar to the Sun, with temperatures up to 10^5 K;

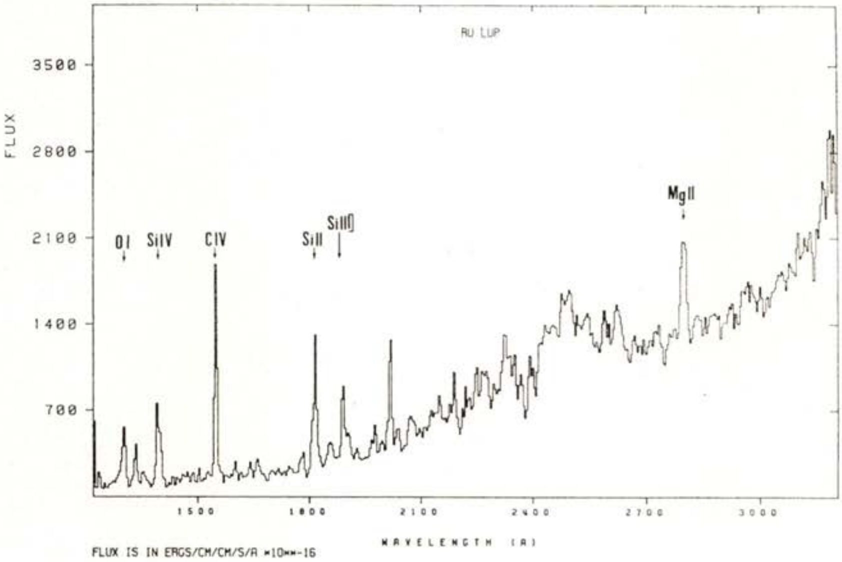

Fig. 3 — Low resolution UV spectrum of RU Lupi in the wavelength range [1200, 3200] Å. The spectrum shown results from the merging of two spectra both obtained with the International Ultraviolet Explorer (ESA-NASA).

— high resolution spectra (Fig. 4) that confirmed the presence of a (strong) stellar wind and have been used to constrain the models developed for this star.

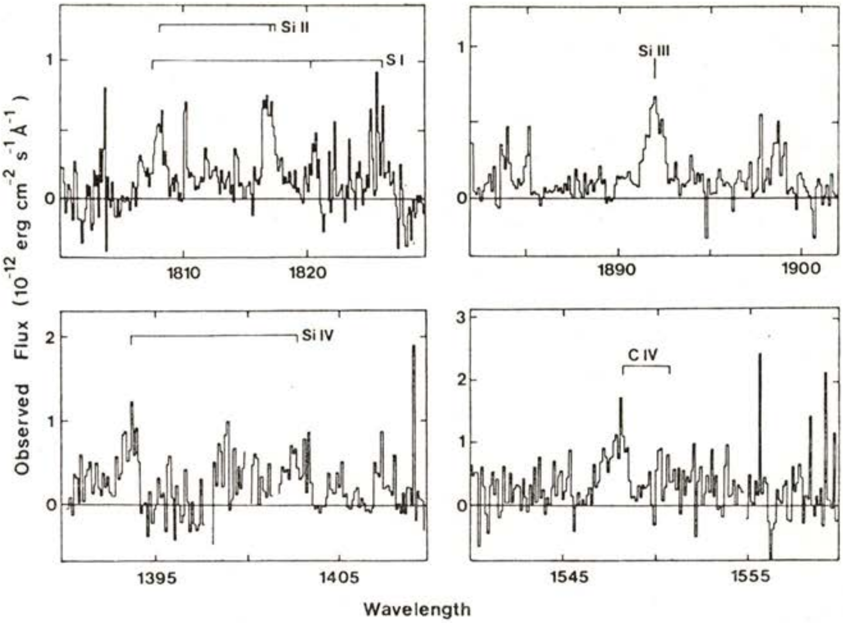

Fig. 4 — High resolution UV data of RU Lupi obtained with the satellite International Ultraviolet Erplorer (ESA-NASA) [8].

From the analysis of the UV observations further information on the atmosphere of RU Lupi is obtained. These results are summarized in Table 1b.

TABLE 1b — Summary of observational constraints of the wind of RU Lupi resulting from the UV data analysis.

	Mg II, Si II	Si III], C III], Si IV, C IV
density (cm^{-3})		10^{10}
temperature (K)	10^4	5.10^4 - 10^5
velocity (Km s^{-1})	240	150 - 170

3 – A MODEL FOR RU LUPI

From the analysis of all the available data the following picture of RU Lupi emerges:

a central star of mass ~ 1 $M_{\odot}$, radius ~ 1.6 $R_{\odot}$ and effective temperature 4400 K, surrounded by a spherically symmetric envelope where the observed emission lines originate; this (geometrically narrow) envelope is not isothermal and can be divided in a chromospheric layer and a higher temperature layer similar to the solar transition region. However the amount of flux coming out of these two regions is highly enhanced relatively to the Sun - RU Lupi emits both in the chromosphere and transition region approximately 10^4 times more energy than the sun. This seems to be a common characteristic for T Tauri stars, however with a variable degree of intensity from star to star.

Therefore, the next logic question to be asked is: do T Tauri stars have such strong coronae as well? The observations one can use to investigate this problem are out of the range of IUE. Therefore one uses both optical observations, searching for the coronal lines of [FeX] and [FeXIV] that are observed in the solar corona, and X-ray emission. These observations would indicate the presence in T Tauri stars of emitting regions of temperature up to 10^7 K. Several searches were done both in the optical ([9], [10]) and in the X-ray using the Einstein satellite [11]. In the case of RU Lupi no detections were made and in more general terms the existence of a corona in T Tauri stars is still a puzzle. Fig. 5 summarizes the result of work done on such topic, not just for RU Lupi but also for other two T Tauri stars previously detected as X-ray sources with the Einstein satellite [12].

Several explanations for the observational results have been proposed, namely,

– the variability of coronal line and/or X-ray emission (may be flare-like outbursts);

– the X-ray mechanism being non-thermal, perhaphs associated with some particle acceleration mechanism-magnetic field lines reconnection, for example.

Meanwhile theoretical modelling has also been attempted. In the model the presence of a magnetic field and linearly polarized Alfvén waves propagating outwards constitute the primary mechanism for driving the wind. Both theory and observations constrain the wind solutions and the overall picture is as follows [13]:

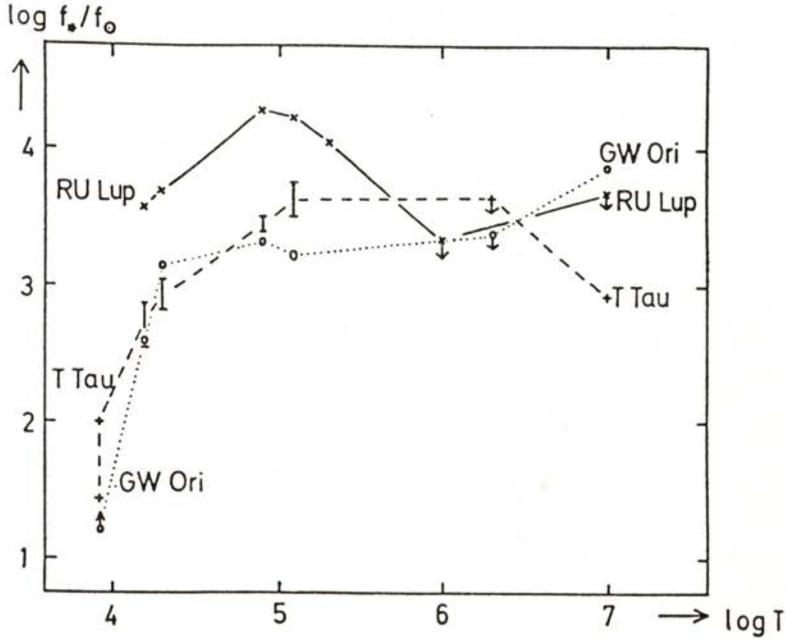

Fig. 5 — Plots of the ratio of stellar to solar fluxes in 3 T-Tauri stars as a function of temperature [8]. This figure shows firstly that the distribution of material with temperature in the outer regions of these stars is different from that in the Sun (i. e. the ratios are not constant with temperature).

— the wind velocity starts with very low values near the base of the chromosphere but (due to the presence of the waves) accelerates very fast reaching velocities of the order of 240 Kms^{-1} quite close to the stellar surface. In order to explain the observed stratification in the widths of the lines dissipation of the waves is assumed to occur before the flow velocity reaches the escape velocity [14]. Therefore the wind will decelerate afterwards due to the gravitational forces. The higher excitation lines would be produced in the decelerating region. The IUE high resolution observations have confirmed such expectations since CIV, SiIV, SiIII] and CIII] are observed to be narrower than the strong MgII, CaII and Balmer lines [8].

This model is able to reproduce the velocity-distance relationship suggested by the optical line profiles and also the rather restricted density requirements imposed by the observations. It seems able to reproduce as well the line profiles observed for the hydrogen lines used to test the model. Furthermore, it suggests a possible explanation for the variation of the temperature through the line emitting region: the heating occurs as a result of the wave energy dissipation (over a short range of distances from the star surface) due to the density gradient. Further theoretical and observational work is being done, respectively the inclusion of a realistic dissipation mechanism while considering the energy problem in the stellar atmosphere and the study of variability. Through the study of variability, simultaneously in the chromosphere and transition region, we will be able to understand what causes the variations (changes in opacity or/and physical changes in the stellar atmosphere). Furthermore the time scales involved will probably provide a very severe constraint to the candidate mechanisms for wind driving and heating.

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