IUE OBSERVATIONS OF YOUNG VARIABLES

Gösta F. Gahm

Stockholm Observatory, S-133 00 Saltsjöbaden

Sweden

ABSTRACT

New insight to the physics and behavior of young variables have been provided by observations with the IUE satellite. These results are briefly reviewed.

INTRODUCTION

A number of far-UV spectrograms of young variable stars have become available through observations with the IUE satellite. Several T Tauri stars and Herbig type Be- and Ae-stars in dark nebulae have been observed and to my knowledge spectrograms of a total of 17 stars, which have been considered to be very young pre-main-sequence stars, are now collected. In many of these cases only part of the spectral region available at the IUE is covered and there are examples where large spectral regions are severely underexposed. With a few exceptions the stars have been observed with the low resolution cameras, providing spectral resolutions of 6 to 7 Å.

Most of the observations lack simultaneous photoelectric and/or spectroscopic observations over the visible and infrared spectral regions. Furthermore, at the initial period of IUE observations, the observers selected primarily objects with very intensive emission line spectra in the visible region. For these stars it is usually extremely difficult to make any precise statements on the dimensions and energy distribution of the star itself and also to derive the value of interstellar extinction and to discuss the influence of possible circumstellar extinction. It is therefore clear that we need much more observations of young variables before their physical properties can be overviewed in more detail.

Nevertheless, the IUE observations have given a completely new insight to the physics and behavior of very young stars, and in the following I will try to extract some of the new information obtained. This review is based on the observations of RU Lup by Gahm et al. (1979), S CrA by Appenzeller and Wolf (1979), T Tau, GW Ori and V 380 Ori by Gondhalekar et al. (1979), RW Aur by Imhoff and Giampapa (1980) and by Cram et al. (1980), DR Tau, CoD - 35°10525 and AS 205 by Appenzeller et al. (1980) in addition to our unpublished observations of RU Lup and DI Cep (G. Gahm, R. Liseau) and of HR 5999 (A. Casatella, G. Gahm, R. Viotti).

MAIN OBSERVED CHARACTERISTICS

The far-UV spectrograms have revealed the presence of very hot and intensive regions around the stars. The ion of highest ionization stage observed in emission is N V at λ1238 Å, requiring some 200 000 K to form. This line is present on DR Tau, CoD - 35°10525 and RU Lup. For this latter star we (Gahm, Liseau and Fredga, unpublished) have set an upper limit to the absolute flux of coronal lines (forming at ~ 10^6K) of < 3×10^6 the solar value.

All T Tauri stars show C IV at λ1548, 1550 Å in emission and in addition the spectral region from λ1150 Å to λ1900 Å is as a rule rich in emission lines of Si IV, Si III, Si II, C III, C II, C I, O I and a number of Fe II lines. Hence, the emitting regions around T Tauri stars cover a large range in temperatures - from 7000 K to at least 200 000 K.

The spectral region from λ1900 Å to λ3300 Å is in some cases dominated by emission lines and in others by absorption lines although the Mg II lines at λ2796, 2803 as a rule are in very strong emission. The particular wavelength at which a transition from essentially an absorption line spectrum to essentially an emission line spectrum occurs is very different from star to star. V 380 Ori of spectral type A 1 is the star of earliest spectral type observed and has an absorption line spectrum all the way down to at least λ1200 Å. RW Aur on the other hand start to show emission lines shortward of 3300 Å (Gahm, 1970). Of course, the critical wavelength of the transition may very well be variable with time.

The emission lines or absorption lines are seen against a continuous emission extending over the entire spectrum. With the exceptions of the stars of earliest spectral type V 380 Ori and HR 5999 (A7 III:e) this continuum is a strong excess continuum over the expected photospheric contribution. So far, there has been no reason to call upon any other emitting process than Balmer continuous emission in the emitting volume around the stars in order to explain the far-UV excess (Gahm et al., 1979; Appenzeller et al., 1980). In the case of RU Lup one has to consider Balmer emission from the hottest as well as the coolest regions.

THE PHYSICS OF INDIVIDUAL STARS

So far, rather little of detailed analysis of the far-UV spectra of the young variables has appeared. The IUE spectra provide information on emission line fluxes and equivalent widths of relatively strong lines only and no information on line profiles, with the exception of the Mg II lines of RW Aur (Imhoff, private communication).

Observations over the visible spectral regions have been obtained simultaneously with the IUE observations for DI Cep (Gahm and Malmort, under preparation); CoD - $35^{o}10525$ and AS 205 (Appenzeller et al. 1980) and HR 5999 (Co-operative project organized by P.S. Thé). We therefore have information on the observed energy distribution from $\lambda1150$ Å to $\lambda5500$ Å (for HR 5999 up to 4.7 μ) for several stars. In the near future we therefore expect presentations of the separate energy distributions of the stars and their emitting envelopes as well as discussions on the separate contributions of circumstellar and interstellar extinction. It is premature at this point to make any statements on these results.

The emission lines can be used as probes into the physical state of the emitting volumes. The diagnostic procedure was developed by Pottasch (1963) and has been used by Cram et al. (1980) to model the emitting volumes around RW Aur and RU Lup. The basic assumption is that both the ionization and the excitation equilibrium of the radiating ions are controled by local conditions. In short, the ionization equilibrium of different ions provides an estimate of the average temperature and also interval in temperature where the emission originates. From the observed fluxes of different lines of different ions the total surface flux is determined after corrections for distance, extinction and dimensions of the star. The emission measure, $\int N_e^2 dh$, is then plotted against electron temperature, T_e, and the resulting relation can be compared to solar values.

In the following we will proceed in a similar but somewhat different way for line fluxes observed for RU Lup during June, 1979 when the far-UV flux of the star was large. According to Gahm et al. (1974) and Gahm et al. (1979) the total visual absorption to RU Lup is $0.3 < A_v < 1.0$. The observed fluxes of different lines forming at different characteristic temperatures (T_{max}) are given in Table 1 where the total line luminosity L_{line} has been computed with an E(B-V) = 0.2 with an average "normal" reddening law according to Savage and Mathis (1979). The last column gives the volume emission measure VN_e^2 computed with the same numerical figures as used by Cram et al. (1980).

The results are given in Fig. 1 where the curve represents the corresponding solar values increased by a factor of 10^6. Also given as crosses are the corresponding volume emission measures of RW Aur from Cram et al. (1980).

The general result, then, is that when treated in this way, the line emission on T Tauri stars behaves very similarly to what is seen on the sun, only that the total emission on these (rather extreme!) T Tauri stars are several orders of magnitude larger than on the sun. Whether this is an indication that the T Tauri envelopes are maintained by similar physical processes that operate on the sun is a question which remains to be explored.

If we had information on N_e for the different temperature zones it would be possible to obtain some idea of the geometrical extent of these zones. For RU Lup Gahm et al. (1974) derived $N_e = 3 \times 10^{11}$ cm^{-3} for lines forming at 10^4 K and lower. For higher temperatures, between 5×10^4 to 10^5 K, the density-sensitive ratios Si III λ1892/C III λ1980 and Si IV λ1403/C III λ1908 can be used (Cook and Nicolas, 1979; Doschek et al., 1978). For RU Lup we obtain $N_e = 2 \times 10^{10}$ for this temperature zone. These simple tools lead to relatively extensive emitting volumes around the stars.

A very important result realized by Cram et al. (1980) from considerations like these is that the suggestion that the 10^5 K plasma in the solar chromosphere-corona transition zone is not directly heated by the local deposition of mechanical energy, but rather indirectly heated by thermal conduction from the 2×10^6 K solar corona, does not apply to T Tauri stars and that "direct, in situ, heating of the 10^5 K plasma must occur".

STATISTICAL RELATIONS

As a complement to the efforts of modelling the physical structure of individual stars we could try to find statistical relations between different observed properties of the 11 stars for which far-UV information exists and in this way hopefully learn something about the nature of young objects. We are presently treating released IUE spectra of such stars in a homogenous way but in the following presentation we must rely also on published or in-print flux-calibrated spectrograms that have been reduced according to somewhat different schemes. Since more accurate comparisons must await a full treatment, I will only give the general results as follows.

1. It is very difficult to find any relation between the appearance of the visible spectrum and any property of the far-UV spectrum. For instance, the absolute C IV flux, as corrected for interstellar extinction and distance (which are uncertain in many cases) does not correlate in any particular way with degree of emission in the visible spectral region, nor does it correlate with degree of ultraviolet or infrared excess.

2. The critical wavelength, λ_{crit}, at which the spectrum changes from an absorption line spectrum to an emission line spectrum was taken by Appenzeller et al. (1980) to be related to the envelope density. This seems to be a reasonable suggestion but I have not been able to find any relation between λ_{crit} and the density-sensitive Si III to C III ratios discussed above. No other relation is apparent such as to the degree of self-absorption in the hydrogen lines or to emission line profiles in general.

3. The character of the light variations and the corresponding amplitudes as given by Herbig and Rao (1972) do not relate in any obvious way to observed characteristics in the far-UV spectrum.

Quite clearly, it will be easier to demonstrate possible relations when more stars are observed. In particular, we need a larger sample of stars for which distances and interstellar extinction can be treated accurately. However, line ratios in the far-UV are relatively independent of these parameters and I find it rather alarming that ratios of lines of for instance C IV, III, II and I do not relate to any other observed property of the star. The intensity ratios of C IV λ1550 Å to Si IV λ1403 Å is very similar from star to star and they fall in the same range as given by Doschek et al. (1978) for coronal hole, quiet sun, solar flares and several late-type stars. Their suggestion that the differential emission measure as derived from the ions in these temperature zones is independent of atmospheric conditions and dependent only on atomic properties of the plasma will then include the rather extreme emitters considered here.

The ratio of Si III λ1892/C III λ1908 is sensitive to density and is plotted as ordinate in Fig. 2. Estimates of the corresponding electron densities are also given. In the left part of the diagram this ratio is plotted against emission class as defined by Herbig (1962). With the notable exception of DI Cep there seems to be a trend such that stars with weak emission line spectra in the visible region have envelope zones at 4×10^4 to 10^5 K of lower densities than those with strong emission line spectra. The relation holds also when the ratios are plotted against equivalent widths of the Fe II emission at λ4924 Å (as taken from Cohen and Kuhi, 1980 and this work), again with the embarrasing exception of D I Cep.

However, the important result is not whether this trend exists or not but rather that in spite of the fact that the objects show such an enormous range in observed parameters like in the degree of emission (the luminosity of the C IV lines ranges over a factor of 100), in emission line widths and profiles, in degree of excess emission and type of variability, the density in the region producing line emission at 5×10^4 to 10^5 K does not differ by more than a factor of 2 or so from the average values, provided that the density scale as given by Cook and Nicolas (1979) is applicable to the T Tauri stars.

If this is true one could start to outline some very interesting implications. However, I find the small range in implied densities very alarming because this is exactly what could happen if the lines were optically thick. In this case the Si III/C III ratio does not provide a useful tool for the physics of T Tauri stars.

THE CAUSE OF THE LIGHT VARIATIONS

The far-UV spectrograms of young variables may provide important information on the cause of the brightness variations with time. The only star that has been followed by repeated far-UV observations with the IUE and ground-based observations over the visible spectral region is HR 5999 (Thé et al. in preparation). The star stayed, however, close to maximum brightness during all IUE observations. This demonstrates the difficulty in having a simultaneous infrared, visible and far-UV coverage of a single star at different brightness levels. Another attempt directed to follow the variations of

DI Cep failed due to bad weather conditions at the ground-based station (Gahm and Malmort in 1978).

We have observed RU Lup on three occasions using the Short Wavelength Prime Camera with an entrance slit of 10x20 sec. on May 18, 1978 and June 17 and 19, 1979. Large variations have occured in the far-UV flux of the star. In spite of this the general appearance of the three spectrograms is very much the same on all three occasions. In fact, if one plots the peak line intensities of lines of different ions divided by the smoothed intensity level of the background continuum as done in Fig. 3 one finds that the line-to-continuum fluxes (ℓ/c) have not changed at all, while the total flux level have changed by a factor 3.5 from May 18 to June 19. In Fig. 3 $I/\langle I\rangle$ represents ℓ/c and for the continuum flux the May 18 spectrogram is set to 1.0.

Now, if the variations are due to violent structural or physical changes in the emitting envelope one needs a rather delicate balance in VN_e^2 throughout the whole region with the different temperature zones. It would mean that the source depths of the different temperature zones change in a rather delicate way as to maintain the general form of the curve presented in Fig. 1 and also to effect strong and weak lines in similar ways. We note that the Si III λ1892 line increased its ℓ/c significantly on June 17, 1979 when the star had intermediate brightness.

A very simple and direct way of explaining this type of variations results if we assume that the dominant cause of the variations is opacity changes in a circumstellar dust layer in the line-of-sight to the star. This interpretation for the variations of RU Lup was also favoured by Gahm et al. (1974) based on photometric and spectroscopic observations at visible wavelengths.

On other stars the dominant cause of the light variations may obviously be intrinsic and all efforts to follow the stars repeatedly, preferably also over visible and infrared wavelengths, should be encouraged.

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TABLE 1. VOLUME EMISSION MEASURES OF RU LUP

Line	λ (Å)	T_{max} (^oK)	Observed flux (erg/cm^2s)	L_{line} (erg/s)	$VN_e{}^2$
C II	1335	20 000	$2.0x10^{-12}$	$2.6x10^{31}$	$5.9x10^{55}$
C IV	1549	110 000	$5.5x10^{-12}$	$6.6x10^{31}$	$7.2x10^{54}$
Si II	1526	15 000	$9.2x10^{-13}$	$1.1x10^{31}$	$8.4x10^{57}$
Si IV	1400	79 000	$2.2x10^{-12}$	$2.7x10^{31}$	$4.3x10^{55}$
N V	1240	200 000	$7.0x10^{-13}$	$1.1x10^{31}$	$9.4x10^{54}$

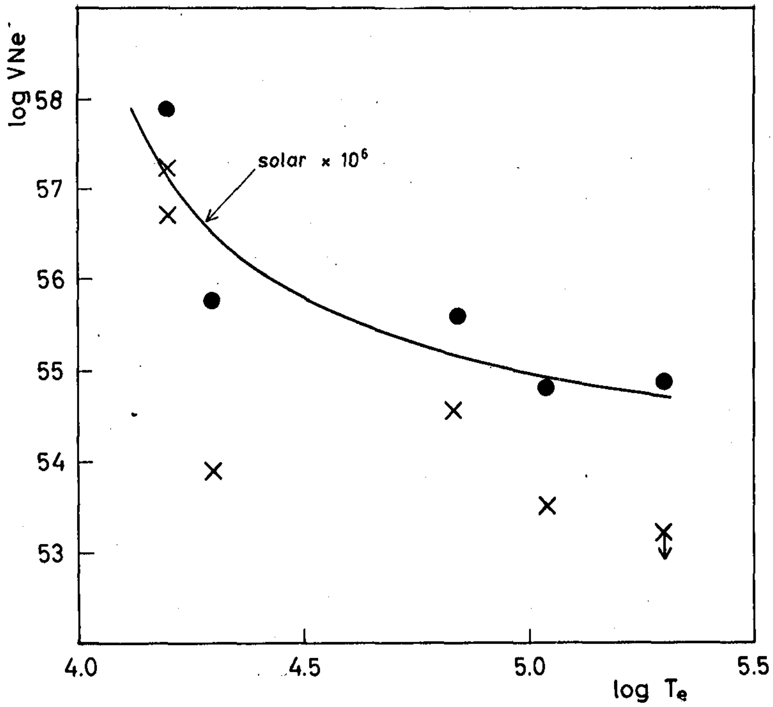

Fig. 1. Logarithmic volume emission measure as a function of logarithmic electron temperature for RU Lupi (filled circles) and RW Aur (crosses).

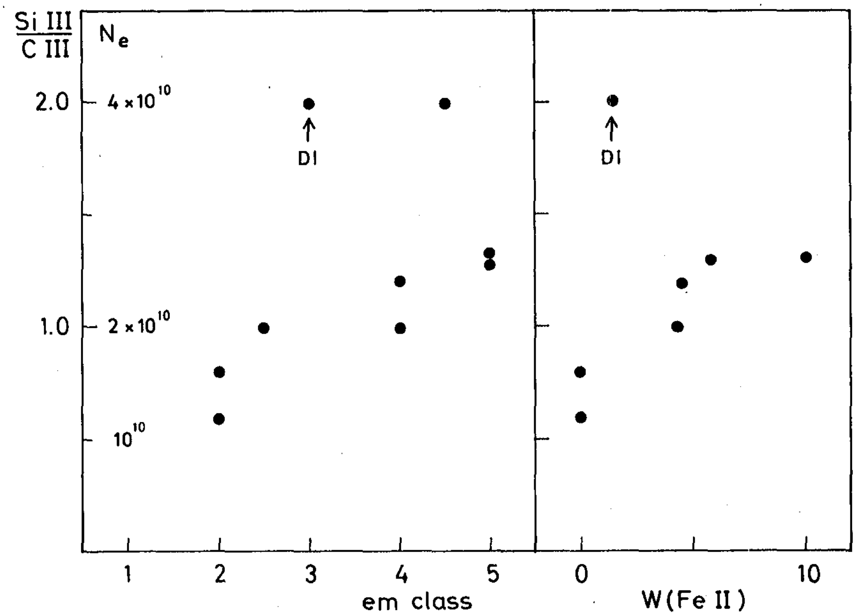

Fig. 2. The ratio of Si III λ1892 to C III λ1908 with corresponding electron densities N_e as function of emission class and the equivalent width of Fe II λ4924. DI marks the position of DI Cephei.

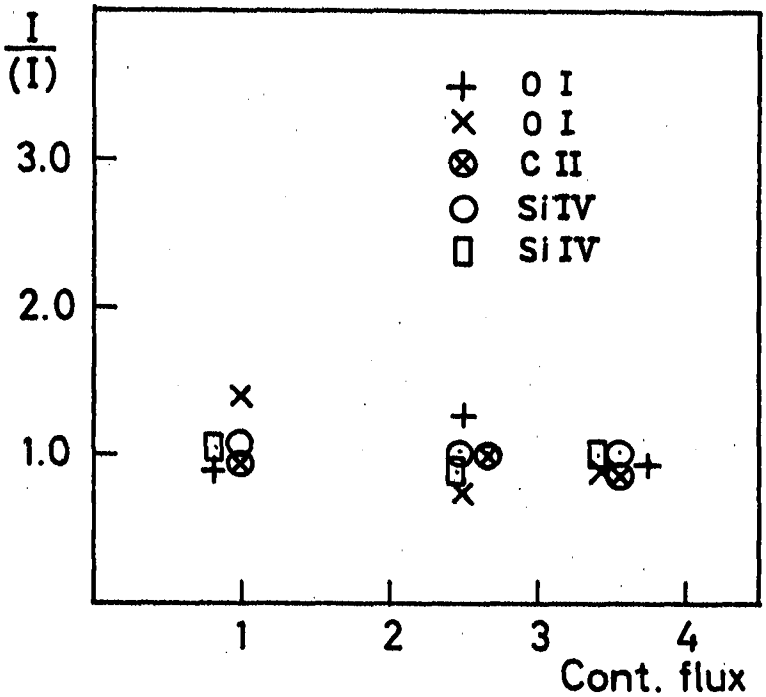

Fig. 3. Normalized intensities of lines of different ions as function of continuous excess flux at far UV wavelengths.