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UV OBSERVATIONS OF MASS TRANSFER IN ALGOLS

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RESUMEN

En este artículo se presentan las principales características de la transferencia de masa en tres ejemplos representativos de los sistemas binarios tipo Algol: U Cep, R Ara y la propia Algol. Para ello se han utilizado observaciones ultravioleta obtenidas con el satélite *IUE*. Se resalta la importancia de realizar medidas continuas durante ciclos orbitales completos así como la información que puede obtenerse del estudio del continuo, las líneas de emisión o las de absorción.

ABSTRACT

Mass transfer patterns in three representative Algol-type binaries, namely U Cep, R Ara and Algol itself, have been derived from ultraviolet observations carried out with the *IUE* satellite. The importance of this kind of measurements covering complete orbital cycles is enlighted as well as the information to be extracted from the pseudo-continuum, emission and absorption lines.

Key words: **BINARIES: CLOSE — STARS: CIRCUMSTELLAR MATTER — STARS: MASS LOSS — ULTRAVIOLET: STARS**

1. INTRODUCTION

Professor Sahade has contributed to the study of interacting binaries with very inspiring works during many years. Within the realm of semi-detached systems, his review of β Lyrae (Sahade 1980) exposed the real problems that we face to understand this peculiar binary, and several papers on Algol binaries with different levels of mass transfer showed the way to extract information from ultraviolet observations about the gas outflows and exchanges taking place (Sahade 1986).

My own research interests in the past have been mainly focused on the determination of accurate absolute dimensions from double-lined eclipsing binaries, to study the internal structure of the component stars, their evolution and composition. Nevertheless, it became clear from several works in the past years that interacting binaries are very important to understand the evolution and content of our galaxy. Moreover, the determination of absolute dimensions and a detailed study of mass transfer in these systems was badly needed to advance in their understanding from a qualitative to a quantitative discussion.

Of course, the lowest levels of interactivity and complexity in close binaries should be used as a first step in the study of the structure of these systems, as represented by the RS CVn and the Algol binaries. Both include non-degenerate components and the more evolved star is still detached (RS CVn) or filling its Roche lobe (Algols). Many important contributions to the present knowledge of active late type stars, like the RS CVn binaries, have been made possible by ultraviolet data but the dynamical study of mass transfer can only be done in Algol systems.

Algol binaries are interacting semi-detached systems with B-to-early-F primary components and less massive, G-to-K secondary companions that are in contact with their Roche equipotential surfaces. They appear to have formed from previously detached binaries in which the originally more massive star evolves off the main sequence, expands to its Roche lobe limit and is losing as well as transferring mass and angular momentum to its companion and the interstellar medium (Algols may in fact contribute with some 20% of the stellar mass expelled to the ISM).

The study in detail of Algol binaries, their formation and evolution, is of fundamental importance in the world of binary stars. First, because they are very numerous, relatively easy to discover, and represent a stage of certain stability when a slow rate of mass transfer has been achieved. Second, Algol binaries represent the simplest approach to more interacting binary systems, were compact objects have already been formed. Understanding the physics of the processes observed in Algol systems will no doubt be of important help to study similar processes in more complicated binaries were reliable observational data are much more difficult to obtain.

In order to have a good understanding of the physical processes of mass transfer, mass loss, stellar evolution, and stellar activity taking place in Algol binaries it is necessary to have accurate observational information of the systems absolute dimensions and the distribution of matter. For the determination of masses, radii, and temperatures of the component stars, a combination of good multicolour light curves with accurate radial velocity measurements is mandatory. An example of possible results that can be obtained using Strömgren *uvby* photometry and high resolution spectrograms have been shown by Helt et al. (1989) for the 3.7 days period semi-detached system BF Cen. This binary, in addition, is a member of the open cluster NGC 3766 what allows an independent knowledge of its age otherwise impossible to derive from the comparison of stellar dimensions with theoretical models. A complete analysis of methods and results in the determination of absolute parameters in Algol-type binaries has been made by García (1990).

For the mapping of the dynamical behaviour of mass transfer between the component stars, or the possible loss of mass from the system, ultraviolet observations of some spectral lines along the orbit is the best available method. Following Sahade (1986), some of the most important informations about Algol binaries obtained with *IUE* are listed below:

- Gas Streams
- High Temperature Plasma
- Turbulent Gas
- Non-Conservative Mass Transfer
- Variable Gas Flows
- Accretion Rates

Ultraviolet observations have therefore been of great importance in the study of Algol systems. They have confirmed the generally accepted model of the gas flow, showing the existence of non-thermal energy sources, as evidenced by the presence of high ionization absorption lines and allowing the study of gas turbulences. Streams flowing from the evolved component have been detected which may impact the other star and circle it, forming a disk, or flow out, forming a circumbinary envelope. Non-thermal energy sources producing the high temperature resonance absorption lines of N V, Si IV or C IV are possibly due to the kinetic heating of the gas as it impacts the surface of the disk. Moreover, UV lines are found to be collisionally excited and perhaps broadened by turbulence. Monitoring of the absorption lines has finally allowed to detect variable flows of gas and, in some few cases, even the estimation of actual accretion rates.

Nevertheless, though *IUE* observations of Algol systems have been important in understanding them, the available data are not sufficient to complete the task of determining the physical properties and evolutionary processes taking place. In fact, there was no satisfactory phase coverage of the most representative systems with *IUE*. The phase coverage that has been achieved is usually obtained by combining observations accumulated weeks, months, or even years apart. This procedure can be particularly misleading because these stars are well known to undergo substantial changes with time. It is important therefore to avoid the use of observations taken at different orbital cycles.

To correct this situation, *IUE* observations have been made around the orbits of three representative Algol-type binaries in different stages of evolution during a non-stop ultraviolet monitoring over 13 *IUE* shifts, or 4 and 1/3 days. A phase coverage of at least one full orbit was obtained thus of Algol, U Cep and R Ara in September 1989 (see details of the program in Giménez et al. 1990) from GSFC/NASA and VILSPA/ESA. Among these systems, Algol was selected as the prototype of the class and because of its relatively slow level of mass transfer and activity, which allows to have a deeper insight into the structure of the component stars. U Cep is another well-known system with significantly higher level of activity and mass transfer, while R Ara is a less well studied binary but represents the initial phases of fast mass transfer with very high activity. In other words, the three systems, R Ara, U Cep and Algol, are bright representatives of the (initial) rapid, (intermediate) moderate, and (final) slow, stages of mass transfer in Algol binaries, respectively. This evolutionary status can be easily seen from the mass ratio of each of them considering that the spectral type of the hotter star is very similar (B7–9V) for the three binaries, allowing an easier comparison among them.

A total of 100 ultraviolet spectra, covering the range 1200 to 3200 Å, at different phases of each system were obtained. Both spectral ranges of the *IUE* satellite were used by means of the LWP and SWP cameras. 17 SWP and 15 LWP spectra were obtained for Algol, 14 and 15 for U Cep, while 19 and 17 were obtained for R Ara. All of them with high resolution. The remaining 3 spectra correspond to low resolution SWP observations of U Cep during the total phase of the primary eclipse, when only the cool star is seen.

The Fine Error Sensor (FES) on board the satellite was used as a photometer to obtain simultaneous optical measures of the stars. Accurate light curves were obtained, with a precision of 0.015 magnitudes, by closely monitoring the sensitivity of the FES with standard stars throughout the observing interval. Though more accurate optical photometry can be obtained from the ground, these measurements permit real-time monitoring of the visual brightness of the stars at the times of the spectroscopic observations. From these data, we have also calculated new ephemerides by computing times of primary minima for Algol, U Cep and R Ara from the photometric measurements and adopting the orbital period from previous studies. The obtained minima are, respectively, Hel.J.D. 2447780.5365, 2447782.604, and 2447779.989 with an average uncertainty of ±0.007 days.

2. THE CASE OF ALGOL

Algol itself (b Per, HD 19356) is the bright prototype of this class of over 500 interacting semi-detached binaries and is one of the best known stars in the sky. It is a triple system in which the eclipsing pair shows an orbital period of 2.87 days and consists of a B8V primary and a less massive, K0–2 IV secondary in contact with its Roche equipotential surface. The third component, an A9/F0 V star, has an orbital period of 1.87 years and is invisible at ultraviolet wavelengths. Algol has been intensely studied and a useful summary of results is given by Sahade & Wood 1978.

The physical and orbital properties of Algol are well determined (see Richards et al. 1988; Kim 1989; Giménez et al. 1990 or references therein). With the available absolute dimensions, a preliminary evolutionary study could be made. The results show that initial masses of 2.8 and 2.5 solar masses, with an initial period of 1.6 days is the most probable scenario leading to the present status of Algol (De Greve 1991). Observations moreover support theoretical models in that conservative mass transfer does not exist.

A comparison of the *IUE* FES light curve with the optical light curve obtained using ground-based photometry by Kim 1989 in the *B* and *V* Johnson's filters, with the same comparison star, shows to be essentially the same. It should be particularly noticed that no dip is observable around phase 0.9 before primary eclipse. This phase corresponds to the largest cross section of the impact site of gas flowing from the cool secondary onto the primary star and the negative detection put constraints on the optical luminosity and contrast of the heated surface. The system Algol thus appears to be quite well behaved and stable from the optical point of view.

On the other hand, ultraviolet pseudo-continuum light curves were constructed from regions of the obtained spectra where no strong features are seen. An average of several pixels around the given wavelength was made with a spectral width of 1 to 2 Å, roughly separated by 100 Å, except for evident spectral features. Again, a good behaviour of the light curves was found in good agreement with the FES optical light curves for all the ultraviolet range observed. As expected, no secondary eclipse could be detected in the ultraviolet. The depth of the primary eclipse was, nevertheless, significantly larger than in the optical range showing the expected brightness ratio increase towards shorter wavelengths. However, a small decrease of around 10% close to orbital phase 0.9 was observed in some ultraviolet light curves. This is the phase where absorption lines reach a maximum due to the visibility of the impact site of the gas from the cool star on the inner hemisphere of the B8V component.

In addition, we have examined the complete pseudo-continuum ultraviolet spectrum around orbital phase 0.32, and fitted the obtained fluxes with a B8V model atmosphere, as given by Kurucz (1979). A very good agreement is obtained with an interstellar extinction of $E(B-V) = 0.06$ as also given by Brandi et al. 1989 or Jamar et al. 1976.

This kind of *IUE* observations have been interpreted in terms of mass-accretion processes in which high temperature (10^5 K) plasma is produced by kinetic heating of gas impacting onto the surface of the hotter component (see Giménez et al. 1990; Guinan, 1989; González-Riestra et al. 1991). The small mass ratio, q = 0.22, of the system indicates that Algol is in the final slow stage of mass transfer and mass loss. This terminal stage appears to be the most common and longest for Algol-type binaries. As in the case of previous studies of Algol (Cugier & Molaro 1988), the *IUE* spectra show strong phase dependent absorption lines of highly ionized species like Si IV, C IV and NV (but no He II). These high-ionized lines are not present in the spectra of late B-type stars and are due to the presence of hot gas flowing from the cool star and interacting with the B8 companion. During our observing interval, we were able to observe Algol over 1.5 orbits, thus covering some phases twice, and we found excellent repeatibility in the strength of the lines at similar phases indicating fairly stable conditions in the gas flows. In fact, the comparison of spectra at similar phases showed good repeatibility even with spectra retrieved from the *IUE* archive corresponding to observations made one year before.

We also found enhanced in the ultraviolet spectra of Algol other less high temperature species, like C II, Al III, Fe II, and Mg II (corresponding to around 10^4 K). All of them, as well as the super-ionized absorption lines of Si IV or C IV, show a strong phase dependence reaching a maximum strength around orbital phase 0.9 and a weakest value between 0.2–0.6 in phase. The strong enhancement of the lines at phase 0.9 can again be interpreted in terms of the visibility of the impact site on the trailing hemisphere of the B8V star. In fact, the partial eclipse of the Si IV 1394 emmitting region starts at the same time as the body eclipse of the primary star as evidenced by the rapid changes with orbital phase.

From the relative intensities of the measured lines it is clearly seen that the resonance C IV lines are much weaker than those of Si IV. But the opposite situation should be present if we are dealing with normal chemical compositions. Nevertheless, this is a common feature of Algol-type binaries which have evidences of a gaseous ring (Sahade 1986). The gas flow pattern of Algol itself does not include in principle a gaseous ring but a stream of matter between the two stellar components. Several evidences, however, suggest that it may exist a low density accretion disk around the B8 primary component.

The radial velocity variations of the Si IV and C IV lines are clearly in phase with the variations of the center of gravity of the primary component. The radial velocities of C IV were measured from the feature at 1548 Å, because the other component of the doublet is blended with three Fe III lines. Therefore, it is natural to adopt that the location of the hot region is connected to the surface of the primary star. Nevertheless, differences in the Doppler shifts relative to the motion of the hotter component, of the order of -50 to -100 km s^{-1} are clearly shown in all orbital phases except around phase 0.9, where small values are observed. The radial velocity of the high-temperature emitting region is generally more negative than the orbital value with a difference of -50 km s^{-1} shown by the hot region with respect to the center of gravity of the primary star at phase 0.25. This can only be interpreted as the observation of a net gas outflow.

Since the lines are observed at any time, we should accept that hot gas moves around the hotter component with a net outward flow. The radial velocities of the lower temperature species are more difficult to measure due to their presence in the atmosphere of the B8V star. On the other hand, the asymmetries and the width of the lines indicates turbulence flows with velocities of the order of 400 km s^{-1}.

Finally, the chromospheric emissions h and k of Mg II, at 2800 Å, also showed the same phase dependence with a maximum of emission around phase 0.9 and the weakest values between 0.2 and 0.6. Nevertheless, radial velocities were found in very good agreement with those of the B8V star not showing thus a net outflow. The observed emission are in any case not linked to the cool component which is expected to be chromospherically active as a consequence of fast rotation and a deep convective envelope. Little is known about the probable magnetic activity of the cooler component of Algol because of the brightness superiority of the B8V component. But G to K stars of Algol-type systems are similar to RS CVns and should have similar levels of activity as indicated by X-ray or IR observations. In fact, accurate VLBI photometry, with resolution better than 1 marcsec, identified the radio emission of Algol with the cooler component (Lestrade et al. 1993).

3. THE CASE OF U CEP

U Cephei is a more active semi-detached binary which consists of a B9V primary and a G8III secondary, with 4.2 and 2.8 solar masses respectively. The G star is evolving and losing mass to its companion and outside of the system, but some of the matter returns to the G star.

The FES light curve was derived in the same way as that of Algol and again compares quite well with the corresponding optical light curves obtained from ground-based observatories. U Cep is thus relatively stable in optical wavelength ranges, at least within the uncertainties of the present measurements. The optical light curves, nevertheless, show clearly a light depression before primary eclipse and a light increase around phase 0.7, both effects probably due to the accretion process.

The same type of evolutionary comparison with theoretical models carried out with Algol using the absolute dimensions of the component stars could not be made with the same quality due to both the uncertainty in the dimensions and the evolutionary status of U Cep. Preliminary results anyhow show that a significant net loss of mass and angular momentum of the system should have occurred.

When we look to the ultraviolet fluxes of U Cep at different orbital phases, avoiding regions with strong spectral features, it is immediately seen that the same repeatibility detected in the case of Algol is not present for the same phases one cycle apart. It is also observed that the phase variation of the continuum in the long wavelength range of the *IUE* spectrometer is larger than in the short range. Thus, higher levels of activity are detected in U Cep.

The gas stream is seen in the resonance Fe II (at 2600 Å) and Mg II (at 2800 Å) lines. Mapping the gas dynamics from the line intensity variations shows that the gas stream circles the B star, some matter falls on it, and the rest leaves the system and partly falls back in the G star. On the other hand, the absorption lines are observed to be broad and shallow indicating a rapid rotation of the hot star of around 300 km s^{-1}.

But the behaviour of the highly ionized Si IV and C IV emissions are in clear contrast with the same lines observed in Algol. First, they are found to be much stronger than in the prototype binary, even in the weak phases. In addition, the phase dependence of the lines does not repeat from orbit to orbit. All lines are observed to be more complex and intense at the start of the our run than one orbital cycle later. There may have been an outburst at the beginning of our observations in which a large amount of mass was ejected from the system. This interpretation is supported by the radial velocity study of the same lines which shows large negative values at the start of the observing run.

Another interesting feature of U Cep is the shape of the short wavelength *IUE* spectrum during the total phases of the primary eclipse (see Giménez et al. 1993). At first glance, the spectrum looks very similar to those obtained in the same spectral range for the late-type active components of RS CVn binaries. This should not be surprising since, at this phases, only the cool secondary component is expected to be visible. Nevertheless, there are some clear differences. The most striking of them is the obvious absence of any He II emission line at 1640 Å. The other is the strength of the emission lines, far larger than in chromospherically active late-type stars. Moreover, the relative strengths of the emission lines indicate CNO processed matter. The consequence is that a chromospheric origin of these lines is very unlikely as already mentioned by Plavec (1983). In fact the lower temperature chromospheric lines appear to have normal surface fluxes, like the Mg II emissions, and scaling the expected value of the He II line with the observed Mg II, it is actually found that the He II feature should not be observable. The apparent absence of this line is then due to its comparison with the very high intensity of the other emissions.

Strong emission lines may be produced by accreting matter around the bright component which is not totally eclipsed and are not due to late-type stellar activity. In the somehow similar semidetached binary SX Cas, with intense mass transfer episodes, the ultraviolet continuum disappears during total eclipse but the ultraviolet emission lines remain.

4. THE CASE OF R ARA

This is an unusual eclipsing binary which is thought to have been caught during the dynamic mass flow stage when the more massive star is still evolving off the main sequence and losing mass. This is a very elusive evolutionary phase leading to the less active scenario represented by U Cep and, later, a slow mass transfer from the now only originally more massive star to the relatively unevolved companion.

The light curve obtained for the system R Ara using the *IUE* FES shows important photometric distortions, evidence of high levels of activity in the accretion process. The FES light curve clearly shows the presence of a secondary eclipse, at phase 0.5, which is not easy accretion process. The FES light curve clearly shows the presence of a secondary eclipse, at phase 0.5, which is not easy to detect due to the strong photometric variability of R Ara. On the other hand, the light curve clearly shows a light increase just before primary eclipse in contrast with the light depression observed in U Cep at the same phases. When compared to previous optical light curves obtained from the ground, significant differences are seen which denote a non stable nature of the binary system (see e.g., Banks 1990) and long term variability. The ultraviolet light curves also show strong variations and a light depression is observed after phase 0, instead of before, in the ultraviolet denoting the presence of thick absorbing plasma.

The ultraviolet spectrum is also complex and very variable. Strong absorption lines of C IV, Si IV, or N V are observed comparable in intensity to those detected in U Cep. This reflects that the amount of gas around U Cep and R Ara is typically about 1.5 to 2.0 times higher than observed on Algol. But in the case of U Cep, the rate did not repeat after just one orbital cycle and the observed value may not represent a typical average being this actually between the Algol and R Ara cases.

The phase dependence of the absorption lines is quite different from that observed in U Cep or in Algol. Though it is difficult to determine a clear pattern of the variations due to superimposed cyclic changes, the minimum of equivalent width appears to coincide with orbital phases 0.25 and 0.75 while the maximum is observed at 0.45 and an eclipse is detected at 0.0 phase. This variations could be interpreted as a flow of hot gas from the more massive to the cooler companion. Radial velocities were also measured and indicate variable outflowing plasma at speeds of around 200–400 km s^{-1} at all phases except primary eclipse.

The observational and data analysis work as well as their interpretation presented in this contribution is part of a long term research program to study mass transfer dynamics in Algol-type binaries together with Profs. E.F Guinan, Y. Kondo, and J. Sahade.

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