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LEFT OVERS FOR DINNER

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RESUMEN

Se han examinado espectros de alta relación señal/ruido en 30 Å mm^{-1} de sistemas binarios en los cuales se pueden esperar efectos de colisión de vientos. Se ha dirigido la atención a rasgos espectrales presentes en las observaciones, que son adicionales a los que pueden formarse en las estrellas que componen estos sistemas. Estos rasgos **sobrantes** parecen formarse en plasma que es expulsado de las estrellas en forma de vientos; pero también podrían deberse a discos remanentes del proceso de formación estelar.

ABSTRACT

High S/N Reticon spectra at 30 Å mm^{-1} of binary systems in which colliding winds may be expected have been examined. Attention is directed to spectral features which are present in addition to what may be formed by the components of these systems. These **leftover** features appear to be formed in plasma which is expelled from the stars in winds; they may be formed also by remnant disks from the star-formation process.

Key words: **BINARIES: CLOSE — STARS: MASS LOSS**

1. INTRODUCTION

Spectroscopic binaries have been studied for more than 100 years. Some show two sets of absorption, and occasionally emission lines, moving in antiphase, while others show the spectrum of only one star; a few show the spectra of three stars. In some cases, additional, extra absorption and emission lines appear. It is these lines which record the physical state and state of motion of the plasma in which the pair of stars is embedded. Bisection of the stellar absorption or emission lines is usually considered to yield the line-of-sight component of velocity of the center of mass of the star forming the lines.

The extra lines have usually been considered to be formed in streams of gas around the stars or in a disk surrounding one or both stars. In recent years, it has become popular to speak of colliding winds as the source plasma for the additional absorption and emission lines seen in the spectra of some binary stars. But is this the primary source?

I shall review information available chiefly about five systems: Plaskett's star (= HD 47129), HD 193793, HD 190918, V444 Cygni, and HD 214419 CQ Cephei. Plaskett's star consists of a pair of massive O stars, while the other systems are O plus Wolf-Rayet pairs. All O and Wolf-Rayet stars possess significant winds. All Population I O and Wolf-Rayet stars may be considered to be young stars, less than about 10^7 years old.

A question which we may ask is this: are the additional features —"left overs"— formed in a disk around one or both stars, in streams of gas in the systems, or in the stagnation ridge between the colliding winds? Most studies assume that the winds are spherically symmetrical. It is usually considered that the winds of Wolf-Rayet stars are denser than those of O stars, but I do not think that this conclusion is proved beyond a doubt. The observed result obtained by using the usually assigned values of $\dot{M}$ is that the momentum ratio $(\dot{M}v_\infty)/(L/c)$, that is the amount of momentum carried by the wind divided by the momentum available in the driving force due to radiation, for Wolf-Rayet stars lies in the range 10–60. Self-consistent models of radiation-driven winds of O stars (see, for instance, Gabler et al. 1989) lead to a value near 0.5. One may question whether the correct value has been assigned for $\dot{M}$ in the case of Wolf-Rayet stars, because if driving by radiation is the only force acting on the wind, the momentum ratio should not exceed unity by a factor greater than a few. A factor larger than about 3 requires postulating a driving force in addition to radiation pressure. Driving by Alfvén waves is a possibility if magnetic fields are present.

It is widely believed that the composition of the winds and atmospheres of Wolf-Rayet stars are anomalous. On the other hand, my spectroscopic studies lead me to conclude that the composition of Wolf-Rayet outer layers may be solar. What appears to be anomalous is the electron temperature in the Wolf-Rayet line-emitting regions. In the case of WC stars, the electron temperature appears to be of the order of 50 000 K or a little higher, while for WN stars, the electron temperature is still higher, possibly as high as 100 000 K. Wolf-Rayet stars have effective temperatures typical for stars of their masses, i.e., 10–20 $M_\odot$. Such temperatures may be of the order of 20 000–30 000 K. In order to generate a high electron temperature in the line-emitting region, non-radiative energy must be deposited in the line-emitting region. A possible physical process is the transformation of mechanical energy from the field of turbulence present in the atmosphere of the star into heat energy. Such a transformation may be facilitated by the presence of rather small magnetic fields, no larger than about 100 Gauss. A magnetic-field-driven process which will do this is known to be active in the lower corona of the Sun.

I am talking about what are called Population I Wolf-Rayet stars. The spectra of some highly condensed considerably evolved objects look very like the spectra of Population I Wolf-Rayet stars. This means that one does not need a massive star with a dense wind to generate the pattern of emission and absorption lines which is called a Wolf-Rayet spectrum. Similarly, the spectra of some hot condensed objects are of type O. An object which possesses an O or Wolf-Rayet spectrum is not necessarily a member of Population I. One has to consider other properties of the star in addition to its spectral type to decide on its probable stage of evolution. Mass is a very important factor in addition to spectral type.

2. PLASKETT'S STAR = HD 47129

Because Plaskett's star has a period of 14.3961 day and the semi-amplitude shown by the sharp cores in the blue and ultraviolet regions attributed to the primary star is 203.7 km s^{-1} (Stickland 1987; Bagnuolo, Gies, & Wiggs 1992 henceforth denoted by BGW), the mass function is large, 12.6 $M_\odot$.

This implies that the system contains two massive O stars. All observers including Plaskett (1922) have noted that it is very difficult to see the secondary spectrum and to determine a reliable semi-amplitude for the secondary star, K_2. In fact, it is not certain that the secondary spectrum can be detected on every spectrogram. The tomographic studies by BGW suggest that log $L_1/L_\odot = 5.47$, that log $L_2/L_\odot = 5.27$, and that the mass ratio $M_2/M_1 = 1.18 \pm 0.12$. The spectrum attributed to the primary star appears to resemble closely that of HD 188001 9 Sge, an O7.5 Ia star, while that of the secondary star appears to be like the spectrum of the rapidly rotating star HD 210839 λ Cep. According to Underhill (1995), λ Cep is an O6 giant star, not a supergiant.

Wiggs & Gies (1992) have analysed the available observations, including some in the Hα region, and they suggest that the spectral type of the secondary star is O6.2 I, while that of the primary star is O7.3 I. They conclude that the secondary star has the denser wind. Plaskett's star is one of the brightest O-type X-ray sources (Sciortino et al. 1990). Polarisation observations have been made by Rudy & Herman (1978), who suggest that the inclination of the orbit is $71 \pm 9°$ and that the polarisation arises from the scattering of the light from both stars by a region of gas lying between the two stars. The spectroscopy of the system favours the hypothesis of gas between the stars, see Plaskett's (1922) observations of faint wide emission features at Hβ, Hγ, and Hδ, and the observations of Hα by Wiggs & Gies (1992) as well as the observations of Struve, Sahade, & Huang, (1958) and of Hutchings & Cowley (1976).

Underhill (1993) used a Reticon to record at 30 Å mm^{-1} the spectrum observed for Plaskett's star in the yellow-green spectral region; the signal-to-noise ratio was near 300. Underhill noted several spectral features which do not fit well with the picture which has been inferred from the ultraviolet, visible region, and from $H\alpha$ observations reported above. Underhill's spectrogram is shown in Underhill (1993) together with comparable observations of the spectra of 9 Sge and λ Cep. The following is evident:

- 1. The profile of the blended O III λ5592 absorption lines from the two stars of Plaskett's star is shallow and not readily separable into a sharp component from the primary star (as in the spectrum of 9 Sge) and a weaker rotationally broadened profile from the secondary star similar to the rotationally broadened profile which is observed for λ Cep.
- 2. A double emission feature like a combination of the C III λ5696 emission lines of 9 Sge and λ Cep, is not seen. Instead, five weak emission lines are seen. Their identifications and

apparent displacements are given in Underhill's (1993) Table 1. Three appear to be weak N II lines, two moving with the primary star and one with the secondary star. These N II lines are not normally seen in the spectra of Of stars. Perhaps these are formed in regions of colliding winds. One emisssion line is a sharp C III emission feature which appears to be moving with the primary star. There is no C III emission feature which can be attributed to the secondary star. Presumably such an emission line should have an intensity and shape like what is seen in the spectrum of λ Cep and be moving with the secondary star. A broad, pointed emission feature is measured at 5688.73 Å. Its central intensity is about 3 percent of the local continuum. This feature is definitely a "left over". Its displacement from the radial velocity of the primary star is -378.4 km s^{-1}. Underhill (1993) has suggested that it may be a C III λ5696 line formed in a disk-driven winds associated with the secondary star.

The star λ Cep is a giant star, rather than a supergiant, see Underhill (1995); it has a disk as well as a wind. Possibly the secondary star of Plaskett's binary is associated with a similar structure, and it is not so luminous as a supergiant. All the earlier observations of HD 47129 (Plaskett's star) have stressed the difficulty of seeing the secondary spectrum on some occasions and the changing strengths of the secondary lines.

The profiles of the blended C IV $\lambda\lambda$5801, 5812 absorption lines from both components of Plaskett's star and that of O III λ5592 seen on Underhill's (1993) spectrogram agree in indicating that both components of Plaskett's star are rapidly rotating O stars, possibly with a projected velocity of rotation of about 300 km s^{-1}.

The wide, complex emission and absorption feature due to He I λ5876 is shown in Underhill (1993). It consists of displaced absorption cores at -661, -140, and $+126$ km s^{-1} and the remnant of a broad emission line. The classical description of such left overs is that they are formed in streams of gas in the system and in a disk (cf., Struve et al. 1958). The He I λ5876 profile may be formed by the gas between the stars revealed by the polarisation measurements of Rudy & Herman (1978). Hutchings & Cowley (1976) have suggested that the secondary star may be surrounded by a dense disk.

The absorption and emission lines seen in the spectrum of Plaskett's star between 5200 and 5900 Å do not support the conclusion that the primary star is a sharp-lined O7.3 supergiant like HD 188001 9 Sge. Rather each star may be a rapidly rotating O star of moderate luminosity (i.e., each a giant star) with much extra plasma in the system.

The large value of the mass function (which leads to large masses for the components of Plaskett's star) is obtained because the radial-velocity excursions of the sharp strong cores seen in the blue-violet and ultraviolet part of the spectrum are interpreted as reflecting the motion of the *center of mass of the primary star*. However, these cores may be formed in the external plasma which the polarisation observations (Rudy and Herman 1978) reveal. The reader should recall that the sharp Ti II, Cr II, Fe II, and Ni II absorption lines seen in the spectra of some Be shell stars are often referred to as "α Cygni lines" because they look like the absorption lines seen in the spectra of A-type supergiants.

The left overs seen in the yellow-green part of the spectrum, and the shallow rotationally broadened shapes of the O III λ5592 and C IV $\lambda\lambda$5801, 5812 lines, all point toward the presence of two rapidly rotating, not too luminous O stars.

Serious consideration should be given to the possibility that the sharp cores upon which most of the radial-velocity results for Plaskett's star depend are formed in gas outside the photosphere of the primary star. They, therefore, may not reflect accurately the line-of-sight velocity changes of the center of mass of the primary star. A campaign to observe the yellow-green spectral region of Plaskett's star thoroughly for at least one orbital period (14.3961 days) might pay dividends.

The profile of the He II λ5411 absorption line is shown in Underhill (1993). This profile is composed of a wide upper part and a sharp core displaced longward by a small amount. Underhill (1993) observed Plaskett's star at orbital phase 0.8432 using Stickland (1987) elements. The orbital elements of Stickland predict that the radial velocity of the primary star at phase 0.8432 should be $+135.7$ km s^{-1} while, that of the secondary star should be -72.3 km s^{-1}. The measured radial velocity shown by the tip of He II λ5411 is $+123.5$ km s^{-1}, which is close to the value ($+126$ km s^{-1}) shown by the most positive absorption core, shown by the complex He I λ5876 feature.

Two interpretations of the observed He II λ5411 profile are possible:

- (1) The profile is made up of blended He II λ5411 absorption lines from the primary and secondary stars, each of which moves in the manner predicted by Stickland (1987).

- (2) The absorption spike of He II λ5411 is formed chiefly in the external plasma around the binary system. This plasma forms the cores of the ultraviolet lines from metastable levels which were measured by Stickland (1987) and by BGW, and considered by them to be formed in the photosphere of the primary star.

Underhill (1993) —in her conclusions— emphasises the second possibility. She notes that the absorption lines of O III and C IV seen in the yellow-green spectral region are better candidates for true photospheric lines than are the sharp cores selected by earlier observers.

3. O AND WOLF-RAYET BINARIES

Wolf-Rayet stars show very strong emission lines in their spectra in comparison to what is observed from stars of other spectral types. In the case of some Wolf-Rayet stars, the emission lines are wide with $FWHM$ equal to a few hundred km s^{-1}, while in others, the emission lines are relatively narrow. All Wolf-Rayet stars show significant infrared excess radiation and radio fluxes; the latter often measured at 2 and 6 cm. The infrared and radio radiation is generated in large bodies of rather low density, comparatively cool plasma in which the star is imbedded. It is frequently assumed that this plasma is put in place by a dense spherical wind with an electron temperature of the order of 20 000 K. The plasma may extend several hundred stellar radii from the star. The observations of White & Becker (1995) suggest that the infrared and radio emitting plasma is confined chiefly to a thin sheet or disk inclined by a small angle to the orbital plane of HD 193793, WC7 + O5. However, the most common assumption about the radio emission from Wolf-Rayet stars is that the radio-emitting plasma is the residue of a dense spherical wind.

The orbit of the O star of HD 193793 is an ellipse with eccentricity = 0.84 ± 0.04 and a projected semi-major axis of 14.7 AU or 2.20×10^{14} cm (Williams et al. 1990). The flux at radio wavelengths comes from two sources: thermal bremsstrahlung from the full body of plasma including the wind of the O star and from a non-thermal source. When the stars pass through periastron, dust forms which radiates in the infrared. This dust dissipates in a few months. Periastron occurs between phase 0.955 when the O star is in front and phase 0.008 when the O star is behind.

The emission profile of C III λ5696 shows a very broad flat-topped Wolf-Rayet emission feature surmounted by a sharp, weak emission C III line which follows the motion of the O star, more or less, and which may be formed in a ridge of colliding winds.

My remarks about O and Wolf-Rayet binaries which contain WN stars are based on the observations by myself and colleagues of HD 190918, WN4.5 +O9.5I, HD 193576 = V444 Cygni, WN5 + O6, and of HD 214419 = CQ Cephei, nominally WN7 + O. (These spectral types are from the catalogue by van der Hucht et al. 1988). The spectral type of CQ Cephei has recently been revised somewhat by Marchenko et al. (1995). It has been notoriously difficult to detect the spectrum of the companion star in this system. Both V444 Cygni and CQ Cephei are eclipsing binaries.

I and my colleagues have also observed the spectra of three Wolf-Rayet stars, which, so far as we can tell, are single stars: HD 50896, WN5; HD 191765, WN6; and HD 192641, WC7 +OB. We were not able to detect the spectrum of a companion star to HD 192641. My interpretation of the spectra of Wolf-Rayet stars in terms of a geometric model is influenced by all of these observations.

The parameters which result from the solutions for the radial-velocity orbits of binary stars depend upon the assumption that the changes of the line-of-sight component of velocity which are observed by means of the absorption and emission lines of the stars reflect accurately changes in the line-of-sight components of the motions of the cores of the Wolf-Rayet and O stars. The motion of the center of mass of the Wolf-Rayet star may be inferred from the gravitational coupling of the Wolf-Rayet star to the O star. It is possible that the center of an emission line may not be on the same sight-line from the observer as the center of mass of the Wolf-Rayet star is.

In the case of the circular orbit of V444 Cygni (Underhill, Yang, & Hill 1988) the average T_{+ve}(O star) determined from observations of the absorption lines He II λ5411, O III λ5592, and C IV λ5812 occurs on JD2447048.1133 while that shown by the emission lines N IV λ5203 and He II λ5411 occurs on JD2447045.8145. The O star should pass through maximum radial velocity one-half period (2.1062 days) before the Wolf-Rayet star does. The observed difference is 2.2988 days. This implies that, on the average, the light centers of the emission lines pass through maximum positive velocity 0.1962 days later than they should do if the emission lines mirrored the velocity of the center of mass of the Wolf-Rayet star. Clearly, on the average, the light centers of the emission lines lag the center of mass of the Wolf-Rayet star by 0.046 of a cycle.

In the case of the long period (112.4 days), eccentric binary HD 190918 (Underhill & Hill 1994) the light center of the He II λ5411 emission line goes through periastron 10.0 days (0.089 in phase) earlier than the center of mass of the O star does. Thus, in this O + WN binary, the light center of the emission line measured to track (hopefully) the center of mass of the Wolf-Rayet star is not on the line-of-sight from the observer to the position of the center of mass of the Wolf-Rayet star inferred from the orbit of the O star.

In the case of the short-period eclipsing pair CQ Cephei, Underhill, Gilroy, & Hill (1990) were not able to detect any lines in the spectrum of the OB companion. Underhill et al. assumed a circular orbit and found that the average T_{+ve} for the nine features moving with the Wolf-Rayet star which they measured occurred at JD2444366.775. When this time is updated by 2049 cycles in order to match the epoch of the orbital elements of Marchenko et al. (1995) T_{+ve} occurs on JD2447729.683, thus 1.305 days or 0.795 in phase earlier than the time of periastron passage given by Marchenko et al. Those authors find that the semi amplitude shown by the N IV λ4058 line is 303.2 $\pm$ 2.4 km s^{-1} which is almost the same as the 290 $\pm$ 5 km s^{-1}, which Underhill et al. found from their best Wolf-Rayet line, N IV λ5736.94. The γ velocity found by Underhill et al. for N IV differs by a significant amount from the value suggested by Marchenko et al. for N IV λ4058. Underhill et al. found that the γ velocities of the features which they measured spanned a range from +44 to -480 km s^{-1}. This result suggests that the different features formed in the atmosphere of CQ Cephei, and in the plasma in which the binary star is buried, are formed at places where the line-of-sight component of motion of the plasma has widely differing values.

It has been known for a long time (see, for instance, Hiltner 1944) that when the He II emission lines in a WR + O binary are bisected one often finds a velocity displacement of about +100 km s^{-1} relative to the systemic motion shown by the O star, while lines from the C and N ions may show displacements of the order of $-$50 km s^{-1}. Such findings may be interpreted as infall or outflow of the line-forming plasma relative to the systemic velocity of the O star.

4. CONCLUSIONS

The observations of the spectra of O and Wolf-Rayet binaries summarized in the preceding paragraphs imply that the line-forming regions of Wolf-Rayet stars are extensive but are neither homogeneous nor arranged in a spherical symmetrical wind. The O and Wolf-Rayet stars as well as the massive binary system HD 47129 (Plaskett's star) offer many left overs from the standard view of spherically symmetric stars with spherically symmetric winds in collision. These left overs should be considered. A helpful generalisation is that Population I Wolf-Rayet stars are the massive counterparts of T Tauri stars only now arriving on the ZAMS (Underhill 1991). Like many young objects they appear to be imbedded in disks or clouds left over from the star-forming process.

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