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GENERATION OF AN EXTERNAL RING DURING THE 1978 OUTBURST OF WZ SAGITTAE

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ABSTRACT

It has been proposed that the emission lines observed in the spectrum of WZ Sge during its recent outburst originated in a circumstellar gaseous ring surrounding this entire binary system. We suggest a possible mechanism for the formation of this ring. The luminosity of the outburst, near or at the surface of the white dwarf component of the system, stops for a few days the mass transfer from the secondary onto a disk around the primary through the Lagrangian point L_1. The radiation pressure causes instead a flow of mass through the L_2 point to a new ring around the system. A few relevant observations during the outburst episode are discussed and found to be consistent with this model.

Subject headings: stars: dwarf novae — stars: individual

I. INTRODUCTION

The latest eruption of the recurrent nova WZ Sge in 1978 December was extensively recorded spectroscopically (Crampton, Hutchings, and Cowley 1979, hereafter CHC; Gilliland and Kempler 1979, hereafter GK; Brosch, Liebowitz, and Mazeh 1980, hereafter Paper I) and photoelectrically (Brosch 1979; Bohusz and Udalski 1979). Several observers have noted the close similarity of the spectrum of the nova near its maximum light to the one in the quiet state. In particular, the lines Hα and Hβ appear in emission with a double peak structure, while the higher Balmer lines appear in absorption. There is, however, one significant spectroscopic difference between the two phases, on which we focus our attention in this paper. In the quiet phase of the nova, the separation between the two components of the hydrogen emission lines corresponds to a Doppler velocity of ~ 1450 km s^{-1} (Krzeminski and Kraft 1964), whereas during the outburst the observed separation was only ~ 500 km s^{-1}.

It was suggested that the double peak emission during the outburst episode originates in an extended disk or a ring encircling the binary system (GK; Paper I). This idea is based on the fact that the Hα emission line has a typical double peak profile of a disk or a ring (Huang 1972). In particular, each of the two components is very symmetric by itself, as is shown in Figure 1 of GK. This feature is consistent with the usual interpretation that the two components are emitted at the far ends of a ring, as seen by the observer. Another conceivable interpretation is that the Hα profile consists of a relatively narrow absorption, superposed on a single wide emission line. However, this is not applicable here, because the other absorption profiles observed in the system at the higher Balmer lines have a width larger than ~ 1500 km s^{-1} (Walker and Bell 1980; CHC), whereas the peaks of Hα are separated by less than ~ 500 km s^{-1}. In a typical emission profile from a ring, half of the peak separation represents the Keplerian velocity of the ring particles. A decrease in the Keplerian velocity by a factor of ~ 3 would correspond to an increase in the orbital radius by a factor of ~ 9, whence the suggestion for the presence of an outer ring during the eruption (Paper I). The fact that the Hα profile remained constant during the entire binary period (Paper I; GK) is an additional indication for the presence of an outer ring as the source of the profile. In the present paper we develop this idea and suggest a mechanism for the formation of such a ring.

In our model we assume that the outburst took place near or at the surface of the white dwarf (w.d.). The eruption could be triggered either by a burst of mass transfer (Bath and Pringle 1979) or by instability in the inner disk (Smak 1979). It could even have formed by a thermonuclear runaway as is inferred in classical novae (Gallagher and Starrfield 1978). In all cases, the outburst luminosity is generated near the surface of the w.d. We suggest that during the eruption the radiation pressure force associated with the high luminosity stopped the constant mass transfer from the secondary onto the w.d., which presumably was the source of the energy during the quiet state of the nova (Robinson, Nather, and Patterson 1978, hereafter RNP). Between eruptions, the mass transfer takes place at the inner Lagrangian point L_1. However, after the radiation force of the outburst was turned on, the matter expelled by the expanding secondary was forced to flow through the outer Lagrangian point L_2, forming a circumbinary ring around the entire system. This ring may then be interpreted as the origin of the narrowly separated double component emission lines observed near maximum light.

A list of principal phenomena observed during the

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outburst is given in § II, and the proposed model is explained in §§ III–V. Further possible consequences of the model are discussed in § VI. In the last section, a few remaining open questions are briefly discussed.

II. OBSERVATIONS

The following detailed observations are relevant to our model.

a) *Photometry*

1. The optical luminosity of the star increased from an apparent magnitude ~ 14.5 to magnitude 8, probably within a few hours. A slower decline followed with a characteristic time of ~ 15 days (Brosch 1979).

2. The color indices of the nova during outburst were $B - V \approx -0.1$ and $U - B \approx -1$ (Patterson 1978).

3. Light intensity variation in the binary period was observed, superposed on the general light curve of the nova eruption. The binary light curve, which does not resemble that of an eclipsing light source, consists of two maxima. The primary one was observed at phase $\phi = 0.59$ of the preoutburst binary period.[4] On December 6, 7, and 8 the primary peak in the light curve was 0.2 mag above the continuum intensity and it steadily decreased relative to the secondary peak until its eventual disappearance around December 14 (Bohusz and Udalski 1979).

b) *Spectrometry*

4. A few hours after the discovery of the outburst, on December 1.7, Hα was seen in emission with a round structureless profile (Paper I).

5. From December 2 until December 8, Hα and Hβ were presented in emission with a double component profile. The separation between the components was ~ 500 km s^{-1}. The double emission structure was stationary within the observational accuracy (GHC; GK; Paper I).

6. The double component emission lines of the outburst were not observed in a spectrum taken on December 20. On December 22 the line structure of the quiet nova reappeared in the spectrum (GK).

7. A probable *S* wave phenomenon was observed on December 6 and 7 (see Kraft, Mathews, and Greenstein 1962 for a description of the phenomenon as observed in the quiet nova). The amplitude of the wave was $2\,K \sim 800$ km s^{-1}, and its maximum positive velocity occurred at $\phi = 0.28$ (CHC).

Some additional results are described by CHC, GK, and Bohusz and Udalski (1979). They are not in conflict with our proposed model.

III. THE RADIATION PRESSURE EFFECT—QUALITATIVE

In the generally accepted model for the quiet state of WZ Sge (e.g., RNP), matter flows continuously from the secondary star through the Lagrangian point L_1 onto a disk around the w.d. The flow is very probably driven out by a pressure force exerted on the outer layers of the secondary by its inner parts. The gas is accelerated through L_1 because the inner pressure force is unbalanced there (Lubow and Shu 1975).

During the time of the maximum of the outburst an additional force is applied to the stream, once it is exposed to the outburst luminosity, namely the radiation pressure force. Provided that the outburst luminosity is large enough, the flow direction is changed by the new force. Matter that has just passed the L_1 point falls back onto the atmosphere of the secondary. Thus, shortly after the outburst no matter is flowing through L_1, the inner pressure at this point is balanced by the high luminosity emanating from the direction of the w.d.

In order to calculate the reaction of the atmosphere of the secondary star to the new force field which for a few days includes also the radiation pressure force, one would probably have to apply two dimensional (or possible three dimensional) hydrodynamical treatment, taking into account also heat transfer effects within the gas layers that are exposed to the outburst radiation. In this work we are not making an attempt to take such a comprehensive approach.

Instead we shall assume as a first approximation that following a short transient period (the length of which will be estimated in § V) the rarefied outer layers of the atmosphere of the secondary approach a state of quasi-hydrostatic equilibrium. In this state, the outer layers of the secondary are adjusted to a new set of equipotential surfaces whose morphology is determined among other forces also by the radiation pressure force. The new equipotential surfaces may have a topology which is entirely different from that of the surfaces before the outburst. In particular the new Lagrangian saddle point L_1^* may be associated with a potential value which is *higher* than the value at L_2^*. Consequently the new secondary Roche lobe "opens" outward, in the direction of L_2^*, behind the secondary star instead of being open near L_1^* in the direction facing the w.d. If the mechanism responsible for the continuous expansion of the secondary continues to operate essentially unhampered by the outburst event that takes place near the w.d., the outer layer of the secondary would soon reach the L_2^* point. Matter will then be driven out of the binary system through L_2^* by the continuing expansion of the secondary. The situation is schematically depicted in Figure 1, which shows the new limiting surface of the secondary and the opening near L_2^*.

IV. THE RADIATION PRESSURE EFFECT—QUANTITATIVE

For our numerical calculations we shall adopt the parameters of the binary system as derived by RNP: the mass of the system $m_1 + m_2 \approx 0.4\,M_\odot$, the mass ratio $m_1/m_2 \approx 20$, the binary separation $A \approx 3 \times 10^{10}$ cm, the period $P \approx 82$ min, the mass transfer rate $\dot{M} \approx 10^{16}$ g s^{-1}, the radius of the w.d. $R_{\text{w.d.}} \approx 10^9$ cm, and the radius of the secondary 4×10^9 cm. The modification suggested

[4] Throughout this work we shall adopt the binary period and emphemeris of RNP ($P = 0^d.0566878455$, $T_0 =$ JD 2,437,547.72845).

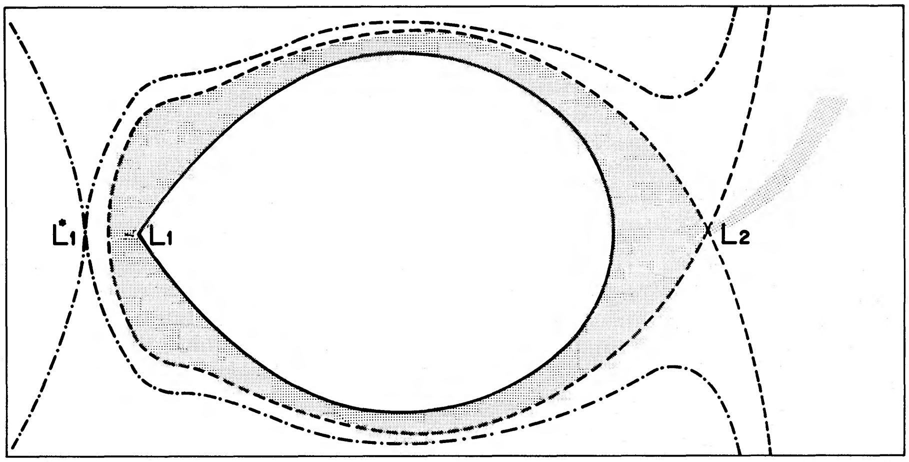

FIG. 1.—Equipotential contours near the secondary star of the WZ Sge system as approximated by eqs. (5). *Solid Line*, in the quiescent state; *broken lines*, in the first few days after the eruption. The shaded area represents the volume into which the outer layers of the secondary have expanded during those few days.

(Fabian *et al.* 1979; Ritter and Schroeder 1979; Smak 1979) will not change our results significantly.

a) *The Outburst Luminosity*

In the first few days after the eruption the *V* magnitude of the nova was ~ 8.5 mag, at least 6.5 mag above the quiet state. The *U* magnitude difference was even larger. Adopting for the optical quiescent luminosity $\sim 10^{32}$ ergs s^{-1} (RNP), we get 10^{34}–10^{35} ergs s^{-1} in the optical region for the first stage of the nova. This estimation is consistent with the observation of Gilliland and Kempler[5] (1980) on December 7. For sources within the primary Roche lobe, an *optical* luminosity of 10^{34} ergs s^{-1} must be associated with a temperature higher than 60,000 K. Indeed, even on December 14 UV observation (Fabian *et al.* 1980) showed that the temperature was larger than 30,000 K. At these temperatures the optical luminosity is less than 1% of the total radiated energy. There is, on the other hand, the possibility that the observed optical radiation is reprocessed energy from a larger surface outside the binary system. However, the structure of this surface is a ring, as is evident from the double emission lines. The solid angle subtended by the ring at the w.d. is $\Omega = 2\pi RZ/4\pi R^2 = \frac{1}{2}Z/R$, where *R* is the radius of the ring and *Z* is its height. Inserting $Z \approx 0.03R$ as in accretion disks (Pringle and Rees 1972), we obtain $\Omega = 0.01$. Thus the ring intercepts only about 1% of the total energy emitted from the w.d. In both cases we get $\sim 10^{37}$ ergs s^{-1} as the outburst luminosity in the first few days of maximum light. Because of the high temperature of the source, most of the radiation is in the far-UV, beyond the Lyman limit. The interaction of this radiation with matter near L_1 results in the ionization of the matter together with exertion of radiation force on the ionized material.

[5] In their caption to Figure 1, 10^{-24} should probably replace 10^{-26}.

b) *The External Radiation Force on Matter near* L_1

In order to evaluate the radiation force, consider a fully ionized *hydrogen* gas at a distance *a* from the source. The force per unit mass exerted by the external radiation through electron scattering is

$$\frac{dF_{es}}{dm} = \frac{0.4}{c}\frac{L}{4\pi a^2} \approx 10^5 \frac{L_{37}}{a_{10}{}^2} \text{ dyn g}^{-1} , \qquad (1)$$

where L_{37} is the radiation in units of 10^{37} ergs s^{-1}, and a_{10} is the distance from the source in 10^{10} cm.

The force per unit mass due to ionization is

$$\frac{dF_i}{dm} = \frac{h\bar{\nu}}{c}\xi ,$$

where $\bar{\nu}$ is the average frequency of the ionizing photons and ξ is the rate of ionization per unit mass. In a steady state, ξ is equal to the rate of recombination per unit mass. In a fully ionized gas this rate is given approximately by $m_p{}^{-1}N\alpha$, where m_p is the mass of the proton, *N* is the number density of the atoms in the gas, and α is the recombination coefficient of hydrogen. Therefore,

$$\frac{dF_i}{dm} = \frac{h\bar{\nu}}{c} N_{av} N\alpha .$$

Taking $h\bar{\nu} \geq 13.6$ eV and $\alpha \approx 4 \times 10^{-13}$ cm^3 s^{-1} (Allen 1973), one gets

$$\frac{dF_i}{dm} \gtrsim 1.7 \times 10^5 N_{15} \text{ dyn g}^{-1} , \qquad (2)$$

where N_{15} is the number density in units of 10^{15} atoms cm^{-3}. Thus the force per unit mass in fully ionized hydrogen due to ionization is independent of the incident flux.

To find the conditions under which the ionization effect is stronger than that of electron scattering we compare expressions (1) and (2). The exact value of the numerical coefficient that should be substituted in the right-hand side of expression (2) in order to change it into an equality depends on the spectral distribution of the ionizing radiation beyond the Lyman limit. We obtain at the Lagrangian point L_1 which is at a distance $a \approx 2 \times 10^{10}$ cm from the w.d.:

$$L_{37} \leq 7N_{15} . \quad (3)$$

Thus, if the density of the ionized gas is 10^{15} or larger, the ionization of hydrogen atoms is the dominant process unless the luminosity of the outburst is 10^{38} ergs s^{-1} or larger. In our treatment of the radiation pressure we therefore consider only the force due to the ionization of hydrogen. We note here that as all the external incoming radiation is absorbed at L_1, the external radiation pressure exerted on matter there is

$$P_{\rm ext} \sim 10^5 L_{37} \text{ dyn cm}^{-2} ,$$

whereas the gas pressure is

$$P_{\rm gas} \sim 10^3 N_{15} T_4 \text{ dyn cm}^{-2} ,$$

where T_4 is the gas temperature in units of 10^4 K. Since the stream at the quiet state moves through L_1 with the sound velocity (Lubow and Shu 1975), its rate of momentum transfer is of the same order of magnitude as the gas pressure. Therefore, the radiation at outburst stops easily the initial stream.

c) *The New Equipotential Surface*

To consider the new shape of the secondary due to the radiation force, we use a corotating reference frame, whose origin is at the center of mass of the binary system, whose x-axis is in direction of the secondary, and whose z-axis is in the direction of the angular momentum of the system. We also use $m_1 + m_2$ as the unit of mass, the binary separation A as the unit of length, and $1/(2\pi)$ of the binary period as the unit of time.

The force per unit mass acting on matter ionized by the radiation of the w.d. is written in our dimensionless units as

$$\boldsymbol{F}^*(r) = -\frac{m_1(\boldsymbol{r} - \boldsymbol{r}_1)}{|\boldsymbol{r} - \boldsymbol{r}_1|^3} - \frac{m_2(\boldsymbol{r} - \boldsymbol{r}_2)}{|\boldsymbol{r} - \boldsymbol{r}_2|^3} + \boldsymbol{r}_{xy} + K\frac{\boldsymbol{r} - \boldsymbol{r}_1}{|\boldsymbol{r} - \boldsymbol{r}_1|} , \quad (4)$$

where $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the position vectors of m_1 and m_2; $\boldsymbol{r}_{xy}$ is the projection of $\boldsymbol{r}$ on the x-y plane and K is the magnitude of the force due to ionization which is independent of r, in regions where the density of the matter is independent of r. With $K = 0$ one gets the force in the quiet state of the system. One zero of expression (4) corresponds to the L_1 point of the system, denoted by L_1^* when $K \neq 0$. One finds that the larger the value of K, the closer is the location of L_1^* to the w.d. For the sake of simplicity, let us assume that the ionized matter lies exactly from L_1 onward, toward the w.d. Furthermore, we shall treat the force in the L_1 vicinity as being parallel to the x-axis. In these approximations, the external radiation force will be

$$\boldsymbol{F}^{\rm rad}(x) = K\boldsymbol{i} \quad (x \leq X_{L_1}) ,$$
$$\boldsymbol{F}^{\rm rad}(x) = 0 \quad (x > X_{L_1}) , \quad (4a)$$

where $\boldsymbol{i}$ is a unit vector in the x-axis directions and X_{L_1} is the x coordinate of the L_1 point. In our dimensionless units

$$K = 3N_{15} . \quad (4b)$$

The old potential function

$$\phi(\boldsymbol{r}) = -\frac{m_1}{|\boldsymbol{r} - \boldsymbol{r}_1|} - \frac{m_2}{|\boldsymbol{r} - \boldsymbol{r}_2|} - \tfrac{1}{2}(x^2 + y^2) \quad (5)$$

will be replaced in this approximation by the potential function

$$\phi^*(\boldsymbol{r}) = \phi(\boldsymbol{r}) - K(x - X_{L_1}) \quad (x < X_{L_1}) ,$$
$$\phi^*(\boldsymbol{r}) = \phi(\boldsymbol{r}) \quad (x \geq X_{L_1}) . \quad (5a)$$

The function ϕ^* defines a new set of equipotential surfaces for the WZ Sge system with a geometry that depends on the value of K. In particular, there would be a new limiting secondary surface that will run through either the L_1^* the L_2 Lagrangian points, whichever has the lower value of ϕ^*. A necessary condition for matter to flow through L_2 is that

$$\phi^*(L_1^*) > \phi^*(L_2) . \quad (6)$$

With the parameters adopted for the system, one gets that in the dimensionless units equation (6) is equivalent to the condition

$$K \gtrsim 1 . \quad (7)$$

This condition is easily achieved if

$$N_{15} \gtrsim 0.3 \quad (7a)$$

near L_1.

Note that for the sake of simplicity we have neglected the part of the outburst radiation which acts on points of the secondary surface with $x > X_{L_1}$. This part of the radiation exerts an additional force the effect of which is to push matter toward L_2. Therefore the real lower limit on N_{15} is smaller than in expression (7a). Near the lower limit of N_{15} electron scattering becomes significant again and tends to decrease the lower limit even further.

d) *The Depth of the Ionized Slab*

A sufficient condition for our model is that in the quasi hydrostatic equilibrium attained by the star after outburst, most of the gas above L_1 has been indeed ionized by the external luminosity. To calculate this condition consider a slab of gas of density N at a distance a from the radiation source. The width d of the ionized region is given by

$$\frac{L}{4\pi a^2 h\bar{\nu}} \sim N^2 \alpha d , \quad (8)$$

or

$$d \sim 2 \times 10^8 \frac{L_{37}}{N_{15}{}^2} \text{ cm} , \qquad (9)$$

or

$$d \sim 0.01 \frac{L_{37}}{N_{15}{}^2} \qquad (9a)$$

in our dimensionless units.

We now require that at a distance d above the L_1 point the value of the new potential function will be equal to the potential value at L_2. Since with the RNP parameters of the system

$$\phi(L_2) - \phi(L_1) = 0.03 ,$$

this requirement implies the condition

$$dK \geq 0.03 . \qquad (10)$$

Using expressions (9a) and (4b), we obtain

$$3N_{15} \cdot 0.01 \frac{L_{37}}{N_{15}{}^2} \gtrsim 0.03$$

or

$$L_{37}/N_{15} \gtrsim 1 . \qquad (11)$$

Thus, if expressions (7a) and (11) are satisfied, all the conditions for the outflow of matter from the secondary star through L_2 are fulfilled: the outer layers of the secondary above L_1 are ionized, reaching in height the point where the potential value is equal to $\phi(L_2)$. Further expansion of the secondary under these conditions is limited by the sink which is now near the L_2 point.

Using the Lubow and Shu (1975) order of magnitude estimation, we get $N(L_1) \sim 10^{16}$ atoms cm^{-3} at the quiet state of the nova. However, due to the huge outer radiation, the temperature of the secondary outer layers increases considerably after the outburst. The temperature must rise above 30,000 K in order to radiate as a blackbody the energy it absorbs from the outburst. The Lubow and Shu density estimation is proportional to $T^{3/2}$ and $\mu^{-3/2}$, where μ is the mean molecular weight. Thus the rise of the temperature and the ionization of part of the outer layers bring down the density to less than 10^{15} atoms cm^{-3}. We conclude, therefore, that equation (11) was indeed satisfied during the first few days after the outburst.

V. THE FORMATION OF THE OUTER RING

Since the classical paper of Kuiper (1941), it was known that free particles leaving a binary system through the L_2 point describe open spirals in the rotating frame. However, Shu, Lubow, and Anderson (1979) have discovered that this is not the case in all the binary systems, depending on the mass ratio of the two stars. They have shown that if $m_2/m_1 \leq 0.067$, the orbit of the free particles intersects itself, leading to the generation of an outer ring. Interestingly enough, the RNP ratio for the WZ Sge system falls just at that region. Few authors have criticized the figure of the mass ratio in the RNP model (Ritter and Schroder 1979; Fabian *et al.* 1978; Walker and Bell 1980). According to these authors the mass ratio could be in the region where *free* particles flowing out through L_2 do not form an outer ring. Even in such cases, however, the width of the stream might well cause different parts of the spiral to overlap, forming an "excretion disk" around the system where kinetic energy is being lost through viscous processes. We can calculate the radius of such a disk assuming that no angular momentum is lost on the average before the particles settle in a circular ring around the system. (Huang 1963). If particles are streaming near L_2 on the average in the radial direction with respect to the secondary, the angular momentum per unit mass of the overflowing matter is, in the binary system of units, $x^2(L_2)$, where $x(L_2)$ is the x-coordinate of L_2. A unit mass rotating in a Keplerian orbit in the external ring has the same angular momentum if the radius of the ring satisfies

$$R^{1/2} = x^2(L_2) .$$

With $x(L_2) = 1.23$ we get $R = 2.3$.

The radius of the accretion disk in the quiet nova is $R_d \approx 0.3$. We therefore have $R/R_d \sim 8$, in excellent agreement with the conclusion of Paper I based on the comparison of the emission line profiles before and after the outburst.

We now turn to estimate the time elapsed between the outburst of the nova and the first optical appearance of the ring. First, we have to consider the time required for matter to fill up the new Roche lobe and to reach the L_2 points. The difference in volume between the old and the new Roche lobes is

$$\Delta V \sim 10^{29} \text{ cm}^3 ,$$

and the averaged density might reach

$$\rho \lesssim 10^{16} \text{ particles cm}^{-3} .$$

Assuming as before that the mass loss rate remained during the outburst as in the quiet state, we get

$$\Delta T_1 \sim \frac{\Delta V \cdot \rho}{\dot{M}} \sim 10^5 \text{ s} \sim 1^{\text{d}} .$$

Consider now the time for building the outer ring. If the optical emission of the ring is the reprocessing of UV radiation of the w.d., the ring is observable when its optical thickness to the ionizing radiation becomes 1. We estimate the width of the ring as $\Delta R = 0.1R = 10^{10}$ cm. Taking $L \sim 10^{37}$ at maximum luminosity of the nova, we find from equation (8) that an optical depth of 1 is reached in these dimensions when $N \approx 3 \times 10^{13}$ cm^{-3}. The mass of the ring at this stage is $M \sim 10^{21}$ g when we take, as in § IV, $Z = 0.03R$ for the height of the ring. We get, as before,

$$\Delta T_2 \sim 1^{\text{d}} .$$

This result corresponds very well to the spectroscopic observations numbers 4 and 5 in § II, namely, the absence of the double peaked emission of Hα in the spectrum taken only a few hours after the outburst discovery and the appearance of the feature one day later.

VI. FURTHER POSSIBLE IMPLICATIONS

In this section we interpret some additional observational data that are listed in § II. These interpretations are consistent with our model, although not essential to it.

We first discuss the fate of the accretion disk around the w.d., by adopting as a working hypothesis the assumption that the origin of the eruption is the w.d. We suggest, then, that during the first hours of the outburst, the disk was blown out of the system. In order to liberate $\sim 10^{37}$ ergs s^{-1}, the emitting surface expanded by an order of magnitude, disrupting the existing disk and probably destroying it entirely (Bath *et al.* 1974). The radiation pressure in the few hours following the eruption may also be a very effective means of blowing the disk away from the system.

After reaching a certain maximum radius within the binary system, the expanded photosphere begins to contract, making room within a few days for the creation of a new accretion disk. As long as the outburst luminosity is large enough, the L_1 passage is closed and matter from the secondary flows from L_2. When the outburst luminosity becomes smaller, the L_1 passage reopens and matter begins to stream again onto the w.d. We have estimated that an equilibrium between L_1 and L_2 is obtained when the luminosity is $\sim 10^{36}$ ergs s^{-1}. This luminosity was reached around December 10. We therefore suggest that around that date the rebuilding of an accretion disk around the w.d. was started. This conclusion is also consistent with the observation of Bohusz and Udalski (1979), that around December 10 the photometric binary period of WZ Sge increased sharply by 1%.

It has been suggested by several authors (GK; Vogt 1979; Papaloizou and Pringle 1979) that this increase is related to the superhump phenomenon known to occur in SU UMA stars. In all other known members of this subclass, matter flows through L_1 when the superhump effect is observed. Furthermore, Papaloizou and Pringle (1979) have suggested on theoretical grounds that the flow of matter through L_1 is essential for the superhump phenomenon. Therefore, the onset of the superhump effect in WZ Sge on December 10 may perhaps be regarded as an observational indication of the resumption of accretion of matter into an inner disk around the w.d. This implies that in WZ Sge it took about 10 days to rebuild a line emitting disk around the w.d., since on December 20 no double emission was observed in the spectrum, while on December 22 the structure of the quiet nova reappeared (§ II*b*[6]).

In § II*a*(3) we cited the photometric observations of a binary periodicity in the light curve on WZ Sge following the outburst. We speculate that the primary maximum in the binary light curve is the reflection of the intense radiation near the w.d. from the surface of the secondary star. We have argued that the total luminosity of the outburst is ~ 100 times the optical one. Therefore, the amplitude of 0.2 mag of the primary maximum corresponds to 2×10^{-3} of the total luminosity. If the exposed hemisphere of the secondary is reradiating the energy intercepted by it mostly in the optical region, the solid angle subtended by it at the w.d. must be of the same order, as indeed is the case in the geometry of RNP.

Finally, the possible *S* wave phenomenon, observed by CHC (see § II*b*[7]) may also be interpreted in a consistent way within our model. The particles flowing out through L_2 constitute a gaseous jet near this point. If the flow velocity with respect to the secondary is small, the radial velocity of this jet with respect to the observer is essentially the radial velocity of L_2. With $x(L_2) \sim 1.23$ and the parameters of RNP we find that the radial velocity of L_2 has a half-amplitude of $K = 470$ km s^{-1}. This velocity is in fair agreement with $K = 400$ km s^{-1} of the *S* wave observed during the outburst. The observed phase of the *S* wave is also in general agreement with this picture. In Figure 5 of RNP one can see that if the jet has zero velocity with respect to the secondary, maximum positive velocity with respect to the observer occurs at $\phi \sim 0.2$. This should be compared to $\phi = 0.28$, the observed phase of maximum radial velocity of the *S* wave. The difference may easily be accounted for by a stream of matter through L_2 that has a small, nonzero component of radial velocity with respect to the secondary.

VII. DISCUSSION

We have shown that the bolometric luminosity of the WZ Sge outburst at maximum light was $\sim 10^{37}$ ergs s^{-1}. Since the time scale of the outburst was $\sim 10^6$ s, one gets for the total energy of the eruption

$$\Delta E \sim 10^{43} \text{ ergs} .$$

This is about the nuclear energy of hydrogen-rich matter that was accepted onto the w.d. during the 30 years between outbursts, if we take $\sim 10^{-10}\, M_\odot$ yr^{-1} as the mass transfer rate in the quiescent state of the recurrent nova. Therefore, it seems that, energetically, the nuclear mechanism can be the source of the WZ Sge outburst, as has been suggested for the recurrent and dwarf nova phenomena (Saslaw 1968; Starrfield, Sparks, and Truran 1974).

The energy associated with the outburst is large enough to blow $10^{-7}\, M_\odot$ of the w.d. envelope. On the other hand, no spectroscopic evidence was detected after the eruption for large mass ejection from WZ Sge. Therefore we suggest that perhaps part of the w.d. envelope expanded during the first stage of the outburst to a few stellar radii, disrupting the accretion disk. This expanded envelope was probably the source of the optical luminosity observed.

The scenario faces two problems—one on observational grounds and the other in theory. The observed color of the outburst, $B - V = -0.09$, $U - B = -0.98$ (Patterson 1979), corresponds, in a blackbody approximation, to a temperature of $\sim 15{,}000$ K (Arp 1961). On the other hand, the area of an emitting surface within the binary system is $\lesssim 10^{21}$ cm^2, which requires at least 50,000 K to provide the observed luminosity. This apparent contradiction disappears if the source of the optical continuum is in the outer ring. On the theoretical side, we are not aware of any detailed nuclear model for this type of an outburst, in particular one without mass ejection.

Another difficulty of our model is the observed flickering during the eruption (Patterson 1979). In our model there is probably no accretion disk during the outburst at all and the mass loss from the secondary does not change appreciably. Hence flickering of 0.2 mag when the star is 6–7 mag above its quiet luminosity cannot be explained by the conventional interpretation of instabilities in the "hot spot."

In the previous section we offered an explanation for the primary maximum. However, the interpretation of the binary light curve is not complete because it does not explain the secondary maximum and the possible two unequal minima. To complete it, further elements may be considered, such as the mutual possible eclipse of the w.d. envelope and reflecting hemisphere of the secondary.

Finally, we note that similar conditions for the formation of an external ring as in WZ Sge may be encountered in other interacting binary systems. In particular, these conditions may prevail in a system of a classical nova during its transition from maximum to minimum luminosity. If mass loss from the secondary takes place when the nova luminosity is still greater than a tenth of the Eddington limit, an outer ring may be formed by the same mechanism. Such a ring may infest itself with emission lines in the spectrum of the declining nova.

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