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THE OPTICAL LIGHT CURVE OF NOVA HERCULIS 1991 AND OF OTHER CLASSICAL NOVAE

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ABSTRACT

Observations of an eclipse in the light curve (LC) of the classical Nova Herculis 1991, following its outburst in 1991 March, enable us to decompose the LC into two distinct curves, one of the white dwarf (WD) and one of an accretion disk in this stellar system. It is shown that during the first 50 days after maximum light, the visual LC of the system was dominated by the light of the WD, and that from this time on, the LC is that of the disk. There are two independent observations that support this notion. We suggest that a similar distinction can be recognized in the LC of other classical novae. We also suggest that the oscillations marking the "transition stage" in the declining LC of novae are accretion disk phenomena, akin to the processes in the disks of dwarf novae that give rise to the outbursts of these objects.

Subject headings: accretion, accretion disks — binaries: eclipsing — novae, cataclysmic variable — stars: individual (Nova Herculis 1991)

1. INTRODUCTION

Photometric observations of Nova Herculis 1991, following its outburst in 1991 March, revealed it to be an eclipsing binary system (Leibowitz et al. 1992, hereinafter Paper I). In Paper I it was argued that the primary minimum in the LC of the star is a partial eclipse of an accretion disk around the WD, while the WD itself is not occulted by the secondary star. This coincidental combination of geometrical parameters offers us a unique opportunity to disentangle the contributions of the two major light-emitting sources in the system from one another. With a few additional observations performed in the summer and fall of 1991 and in summer of 1992, we are now able to decompose the observed optical LC into two separate components: (1) the LC of the nova (the WD) and (2) the LC of the disk. We show that the interpretation of the observed declining branch of N Her 91 LC as a combined effect of two distinct light sources, each one undergoing its own evolution in time, is a very likely explanation for the LC of other classical novae as well.

2. NOVA HERCULIS 1991

In Paper I it was shown that the depth of the apparent primary minimum in the LC of N Her 91, when measured in magnitude units, increased with time. We have predicted that the minimum depth will never exceed 0.75 mag; i.e. the occulation will not block more than 50% of the optical radiation of the system. Subsequent observations in 1991 July, September, and October, and in 1992 June and July confirm this expectation. The observational technique employed in all our observations is described in Paper I. Detailed presentation of the newer observations is given in a forthcoming publication (Leibowitz et al. 1993, hereafter Paper III). The new observations also confirm, and enable us to improve, the determination of the binary period of the system. This analysis, however, as well as the derivation of constraints on some of the basic parameters of the N Her 91 binary system, such as the inclination angle and the relative size of the disk and of the secondary star, are deferred to Paper III.

Figure 1 is the LC of N Her 91 over ~500 days. It is obtained by combining the visual estimates of the magnitude of the star as reported in the IAU Circulars in the first few weeks after outburst (empty squares), together with the *R* magnitude measurements performed at the Wise Observatory (triangles). Day 0 is 1991 March 24, the time of the observed maximum light.

About 1″ northwest of the position of N Her 91 in the sky, there is a background star whose image in our CCD frames could not be resolved from that of the nova. In 1992 July, the combined image faded to an *R* magnitude of 17.4, and the contribution of the neighboring star to the total measured light was not negligible anymore. Fortunately the 18.25 red magnitude of this star is known (Humphreys, Zymach, & Stockwell 1991), and therefore its contribution could be removed analytically. Narrow-band photometry around Hα, performed at the Wise Observatory in 1992 June, as well as spectra of the star taken at ESO by M. Della Valle and by H. Duerbeck in 1992 May and 1992 July, enabled us to estimate also that the contribution of Hα and the [N II] emission lines to our measured *R* magnitude of the nova is ~20% (see details in Paper III). Assuming that the source of the emission-line radiation does not partake in the eclipse, we have removed it from the 1992 R magnitude values as well. Thus, the LC presented in Figure 1 displays the "clean" continuum *R* magnitude of the nova.

Figure 2 displays the depth of the primary minimum in magnitude unit, with respect to the magnitudes presented in Figure 1, as a function of time. The uncertainty in the *y* position of each point is ~3 times the size of the square symbol. We see that the trend of increase has indeed leveled off sometime between days 100 and 200 after maximum light, at ~0.5 mag.

It is clear that at maximum light and for some time thereafter, the major light source in the N Her 91 system was the photosphere of the WD, under which the nuclear runaway process was taking place (Gallagher & Starrfield 1978). According to the interpretation suggested in Paper I, the increase in the minimum depth is due to the fading of the uneclipsed nova. The fraction of the contribution to the total light of the system from the eclipsed source, namely from the disk, was accordingly increasing with time. The unchanging

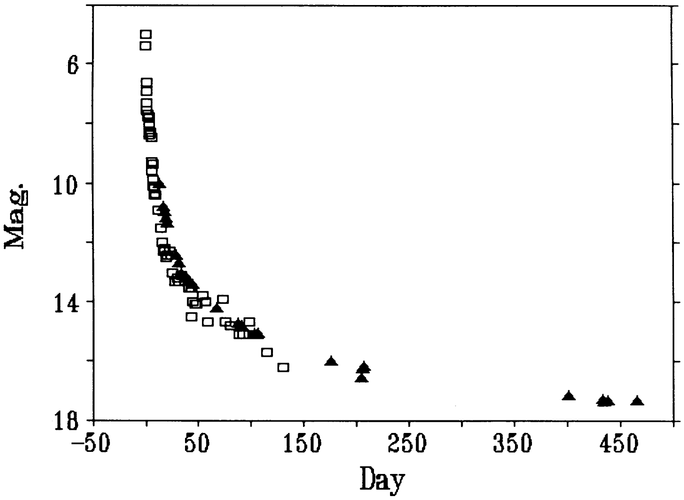

FIG. 1.—Visual (*open squares*) and R (*triangles*) light curves of N Her 91. Day 0 is 1991 March 24 (*maximum light*).

depth of the minimum between days 200 and 500, seen in Figure 2, suggests that in 1992 July, 15 months after maximum light, the major light source is the accretion disk, with practically no optical contribution from the WD. An upper limit of ~0.05 mag can be put on the depth of a secondary minimum that may possibly be identified in the observed LC. We therefore neglect also the light contribution of the secondary star in the system. The apparent depth of the primary minimum in 1992 July is therefore a measure of the fraction of the disk that is being occulted by the secondary star at conjunction.

Consider an axially symmetric thin disk around the WD, coplanar with the binary plane. If we ignore to a first approximation possible luminosity variations across the surface of the disk, then the 1992 July eclipse depth of 0.5 mag means that ~0.37 of the disk area was occulted at conjunction at that time. The presence of a stable luminosity gradient along the disk radius will not change significantly our results and conclusions. Our reference to the area of the disk would then have to be understood as reference to some weighted mean of it. Indeed, the luminosity structure of the disk may on principle be derived from the profile of the primary minimum in the LC (Horne 1985), but this requires observational data with a signal-to-noise ratio that is better than in ours.

The fraction 0.37 of the disk area obscured at conjunction in 1992 was about the same even 15 months earlier, in the spring of 1991. The secondary star in the system, which according to the standard model of classical novae fills up its critical Roche lobe (Patterson 1984), has clearly not changed its size during this period. The width of the minimum in the light curve did change to some extent, from ~0.36 of the binary period in 1991 to ~0.25 in 1992. This change indicates some decrease in the size of the disk. We found, however, that for all possible inclination angles of the system, the implied larger radius of the disk in 1991 yields an occulted fraction at conjunction which is different from the corresponding fraction in 1992 by less than 10%.

Let L and l be the luminosities of the WD and of the disk, respectively, at time t, relative to the luminosity of the system at some reference time t_0. Let α be the fraction of the disk area obscured by the secondary star at conjunction, M and M_0 be the apparent magnitude of the system at times t and t_0, and let D be the depth of the minimum in magnitude units. We have

$$L = (1/\alpha)10^{-0.4(M-M_0)}(10^{-0.4D} - 1 + \alpha)\,, \qquad (1)$$

$$l = (1/\alpha)10^{-0.4(M-M_0)}(1 - 10^{-0.4D})\,. \qquad (2)$$

Figure 3 displays the LC's of the WD (filled triangles) and of the disk (empty squares) of N Her 91, obtained by applying equations (1) and (2) to the observed R LC of the nova (filled squares), with $\alpha = 0.37$ throughout the 15 months of the observations. The luminosities have been transformed back to magnitude units. The curves of the two individual components in Figure 2 cross over around day 50. This means that the principal light source in the system for the first 50 days was the WD, whereas from that time on, the disk light is becoming more important. Eventually, around day 150, the disk dominates entirely the optical output of the system.

We may also allow for a disk with a radius decreasing linearly between 1991 and 1992. The largest difference in the value of α, consistent with $\alpha = 0.37$ in 1992 and with the measured values of the minimum width, is obtained for a disk with

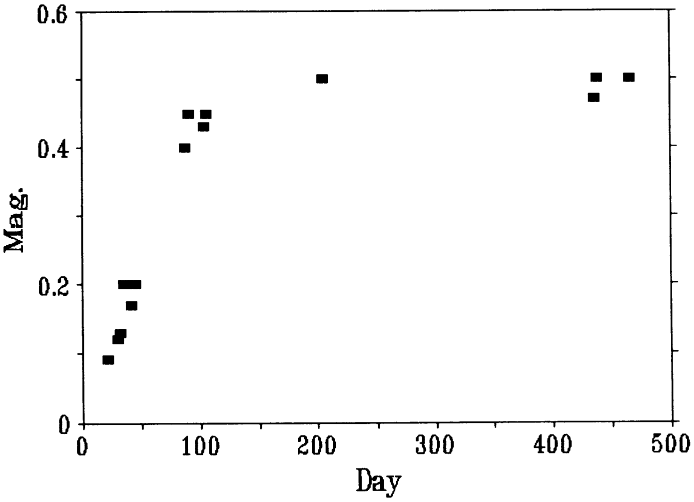

FIG. 2.—Depth of primary minimum in the light curve of N Her 91 as a function of time.

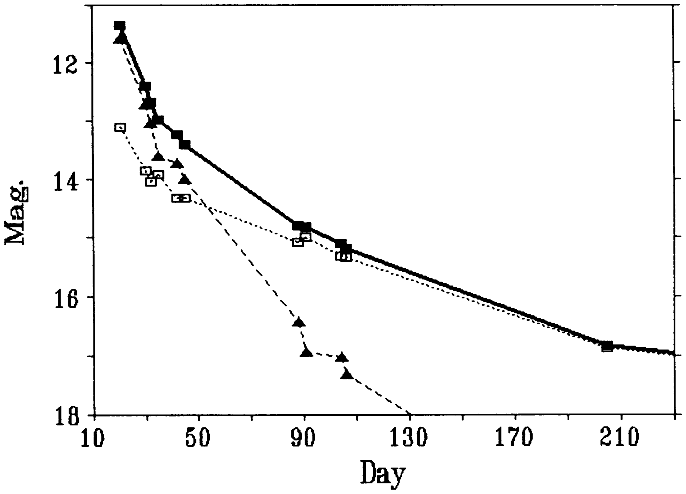

FIG. 3.—Observed R light curve of N Her 91 (*filled squares*) and of the 2 major light sources that combine to produce it. *Filled triangles* present the LC of the WD and *empty squares* the LC of the accretion disk in this binary stellar system.

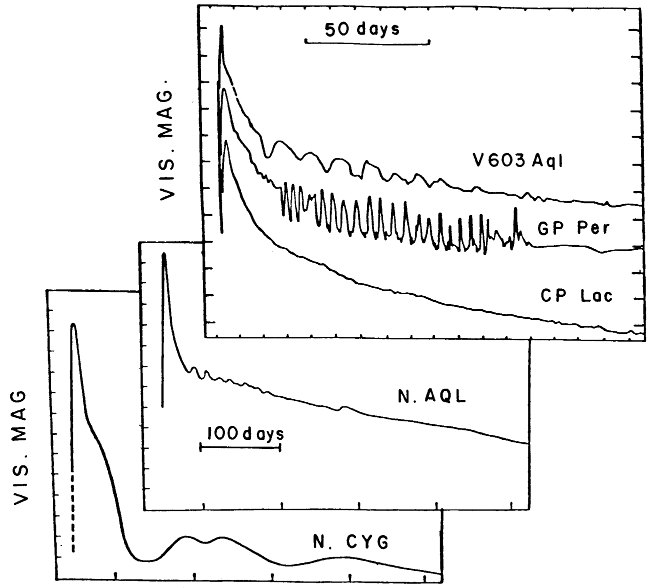

FIG. 4.—Visual light curves of 5 classical novae, N Cyg 1920, N Aql 1918, CP Lac, GK Per and V603 Aql. The LCs are reproduced from McLaughlin (1960), and from Glasby (1969; courtesy of the British Astronomical Association).

a radius smaller than 0.1 of the interbinary distance (see Paper III). Such a disk yields $\alpha = 0.4$ in 1991, and the corresponding crossover of the WD and the disk curves occurs around day 55.

There are two independent observational features that further support this conclusion. In Figure 1 one can see that around day 50 there is an apparent change in the slope of the optical LC of N Her 91. Figure 1 of Paper I shows that around the same time there is also a distinct change in the slope of the $B-R$ LC of the system. These two independent observations are consistent with the notion that around day 50, the two major light sources in the system were about equal in their brightness. The nova dominated the LC at earlier times, and the disk becomes the more important light emitter at later times.

3. OTHER CLASSICAL NOVAE

Figure 4 presents LCs of five other classical novae reproduced from McLaughlin (1960, Figure 2), and from Glasby (1969, Figures 53 and 54). In all 5 LCs there is an apparent change in the slope of the curve a few tens of days after maximum, much like the change observed in N Her 91. In V603 Aql, GK Per, N Aql 1918, and probably also in CP Lac, the change of slope occurs around day 25 after maximum light, whereas in N Cyg 1920 it is around day 50. We suggest that the similar effect has a similar cause, namely that in all these novae, the turn in the LC indicates the time when the WD in each system has faded to a luminosity comparable to that of an accretion disk in the system, and that the curve from that point on is essentially the LC of this disk.

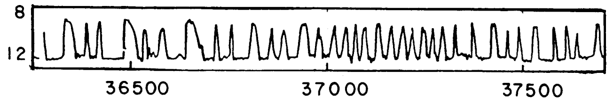

FIG. 5.—Section from the LC of the dwarf nova SS Cyg, reproduced from Mattei (1991).

Some support for our suggestion comes from the following observation. A common feature in the LC of classical novae, particularly the fast ones, is the appearance of a "transition stage," characterized in many cases by semiperiodic oscillations (McLaughlin 1960). A famous example is the LC of GK Per seen in Figure 4. All the explanations of the phenomenon known to us (Bianchini et al. 1992, and references therein), put the origin of the oscillations in the contracting photosphere of the WD, or in processes related to the WD itself. Notice, however, that the oscillations that mark the transition stage appear in the LC of GK Per, as they do in the LC of V603 Aql and of other novae, after the clearly distinguishable kink in the LC. According to our suggestion, this change in the slope of the LC marks the transition of the principal source of the optical radiation in the system from the WD to the disk. Thus, the oscillations that seem to appear on the later branch of the LC, after the change in the slope, are variations in the disk luminosity and are therefore a disk phenomenon rather than a WD photospheric feature.

Figure 5 shows a section of the LC of the dwarf nova SS Cyg (Mattei 1991, quoted in Giovannelli & Martinez-Pais 1991). The similarity between the oscillations of SS Cyg and those of GK Per is striking, although there is a factor of 6 difference between the time and the brightness scales of the oscillations in the two cases. In SS Cyg, the origin of the light variations is believed to be in the disk (Bath 1973; Osaki 1974). We may conjecture, consistently with our interpretation of the gross structure of the LC, that in GK Per, as well as in other classical novae, the luminosity variations during the transition stage originate in the disk as well. Naturally this hypothesis must be tested against past and future photometric and spectroscopic observations of the transition stage in the LC of classical novae.

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