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THE PRESENCE OF AN ACCRETION DISK IN THE ECLIPSING BINARY SYSTEM NOVA HERCULIS 1991 THREE WEEKS AFTER OUTBURST

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ABSTRACT

Photometric observations of Nova Herculis 1991 have been performed at the Wise Observatory, following its recent outburst in 1991 March. We have discovered a local minimum which appears periodically in the light curve of the star. The measured period is $P = 0.29764$ days, and it is most likely the orbital period of the underlying binary stellar system. The width of the minimum of 2.5–3 hr remained constant since it was first detected in April and throughout the following 12 weeks of our observations, whereas its depth increased from 0.1 to 0.4 mag. We interpret the observed phenomenon as an eclipse of a disk around the white dwarf of this nova system, by a much less luminous companion.

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

1. INTRODUCTION AND OBSERVATIONS

The outburst of Nova Herculis 1991 was discovered on 1991 March 24, when it was observed as a 5.4 mag star (Sugano & Alcock 1991). The presumed precursor has been identified on the blue plate of the Palomar Sky Survey as a 20.6 mag star. On the red plate the measured magnitude is 18.25 (Humphreys, Zumach, & Stockwell 1991). Thus the amplitude of the optical outburst is larger than 13 mag, which places this nova among the brightest in recent times.

A key parameter that must be known of any nova that is to be well understood is the binary period of the underlying stellar system. This is why we have decided to make a concentrated observational effort to identify this period, or perhaps other periodicities in the light curve of this star. Beginning 2 weeks after discovery, and during the following 13 weeks, we observed the star photometrically with the 1 m telescope of the Wise Observatory (WO). Table 1 gives the journal of our observations. In all our observations, except the first one which was performed photoelectrically, CCD exposures of 1–2 and of 5–7 minutes in the R and B photometric bands, respectively, have been taken successively. The CCD frames were then reduced with the DAOPHOT photometry program, and the magnitude of the nova, as well as those of neighboring stars, have been measured. From the consistency of the relative magnitude of the reference stars throughout each night, we conclude that until June, the average error in the measured relative magnitudes is not larger than 0.01 mag. In June and July, when the nova was more than 3 mag fainter than in April, our measured relative magnitudes are probably accurate to about 0.02 mag. The results were put on the standard B and R magnitude scale by calibrating the reference stars against Landolt's photometric standard stars (Landolt 1983). The magnitude absolute values are probably accurate to within 0.05 mag.

2. RESULTS AND ANALYSIS

Some of our main observational results are presented in Figures 1 and 2. Figure 1 displays the light curve of the measured nightly average B magnitudes of the star (*filled squares*), as well as the corresponding $B-R$ color index values (*empty squares*). Figure 2 shows all our measured magnitudes in a sample of four of our observing nights. The filled squares denote B magnitudes, and the solid line is a linear interpolation between the measured $B-R$ values.

In nine of our observing nights there is an apparent local minimum in the B and the R light curves (LCs) of the star. Figure 2 shows three of these minima. From the R LCs, we have extracted the times of minima which are presented in Table 1 and indicated by arrows in the three minima displayed in Figure 2. By comparing these times with the corresponding times derived from the B LCs, as well as by eye evaluation of the graphs, we estimate that the maximum uncertainty in the values given in Table 1 is ± 6 minutes. We hypothesized that each minimum point is a signature of a fixed phase in a periodic phenomenon. After correcting the times to heliocentric values, we applied on them the period search algorithm, recently developed by Leibowitz & Leibowitz (1991, hereafter LL). We obtain the following elements:

$$P = 0.297645 \pm 0.000017 \text{ days} ,$$

with epoch

$$\text{JD } 2{,}448{,}443.3263 \pm 0.0011 \text{ days} .$$

We applied the "bootstrap" statistical analysis described in LL and found that the probability that the nine observed events are randomly distributed over the time axis is extremely

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TABLE 1

LOG OF OBSERVATIONS OF NOVA HERCULIS 1991

Date (1991)	Observing Run (UT)	Observed Minimum (UT)	Predicted Minimum (UT)	Minimum Depth (mag)
Apr 6	23.00–26.30		22.70	
Apr 10	23.80–26.20		26.72	
Apr 11	22.93–25.20		24.18	
Apr 12	22.26–26.26		21.78	
Apr 13	22.93–26.20	26.10		0.13
Apr 22	22.23–24.96	24.40		0.14
Apr 25	21.57–26.29	23.75		0.15
Apr 28	21.26–24.13	23.29		0.17
May 2	20.92–26.13		27.20	
May 4	20.75–26.04	22.00		0.20
May 7	20.70–24.15	21.53		0.21
May 30	19.83–25.92		26.70	
Jun 19	18.52–25.58	25.23		0.35
Jun 22	18.06–25.85	24.73		0.13
Jul 5	18.20–25.80	19.90		0.42

minute ($<10^{-5}$). We therefore conclude, at a much better than 99.99% confidence level, that from mid-April and on, there is a cyclic component in the LC of Nova Her 91, with the above period.

The arrow in the April 11 LC in Figure 2 indicates the time point when a minimum with a period P should have occured. In Table 1 we give the predicted times of minima for this, and for all of our other observing nights, in which the predicted minimum has not been covered by observations. In all these nights, except April 11 and possibly also April 6, the structure of the LC observed in the preceding or in the following times is consistent with the notion that a minimum had indeed occured at the predicted times. In the April 11 LC it appears, however, that there is no minimum at the expected time (but see also § 3 about this point). This has caused us to rule out initially the true periodicity of the star (Leibowitz, Mendelson, & Mashal,

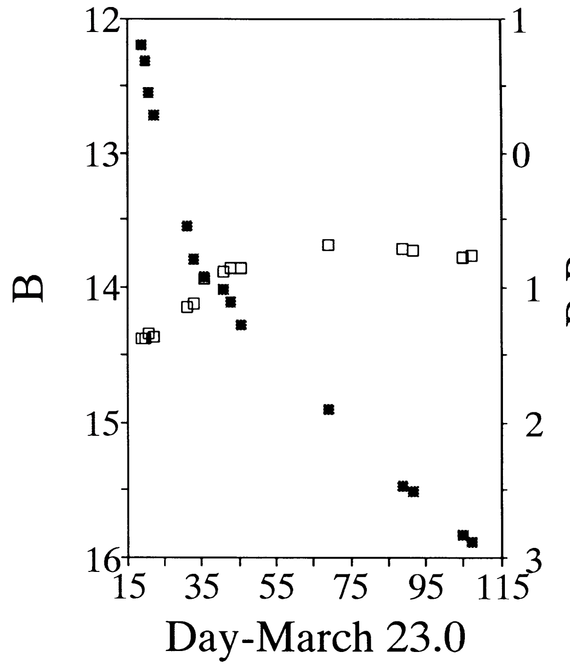

FIG. 1.—Nightly average B magnitudes (*filled squares*) and $B-R$ values (*empty squares*) of Nova Her 91, as measured between 1991 April and July at the Wise Observatory. Day 0 = March 23.0 UT.

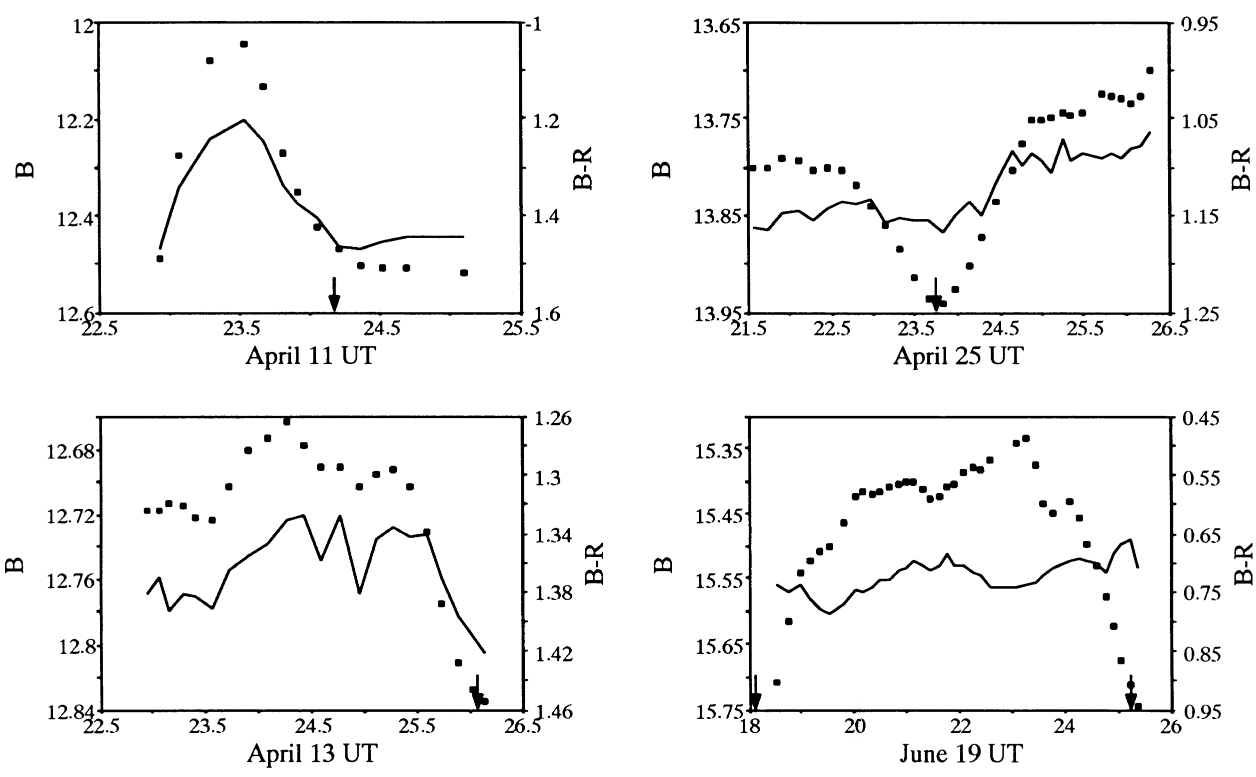

FIG. 2.—Time-resolved B (*squares*) and $B-R$ (*solid line*) light curves of Nova Her 91 in four nights. Arrows in three frames indicate times of observed local minima. Arrow in the April 11 frame indicates time of expected minimum for a 7.143 hr periodicity.

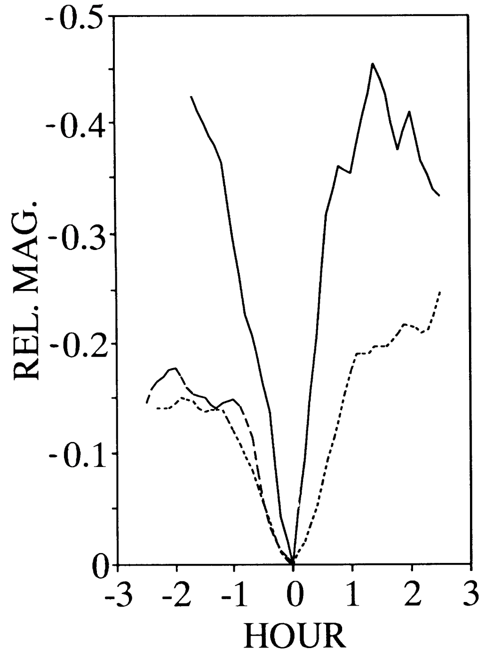

FIG. 3.—Three observed minima in the light curve of Nova Her 91, drawn on the same relative time and magnitude scales. *Dashed line*, April 13; *dotted line*, April 25; *solid line*, July 5.

1991a, b). The realization that the true period is P, the 10th harmonic of our first suggestion, came only on June 22, when we observed for the second time two successive minima in the LC, separated from each other by the time interval P.

Figure 3 displays on a common scale the profile of three of our observed minima: the very first one of April 13 (*dashed line*), the one on April 25 (*dotted line*), and the very last one of July 5 (*solid line*). Although the shoulders of the minima are not always well defined, it is evident from the figure, as well as from the structure of all the other observed minima, that the width of the local minimum in the LC of Nova Her 91, of about 2.5–3 hr, did not change appreciably since it was first detected, until the last of our observations.

Figure 3 demonstrates another important feature of the cyclic minimum in the LC of the nova. It shows that the depth of the minimum (in magnitude units) increases with time. The precise determination of the depth is rather difficult, because of the ill-defined edges of the minima, as mentioned above. Our best estimates for the depth of the observed minima, as given in Table 1, are therefore not accurate to better than 0.05 mag. The trend of increase in the depth is however unmistakable, and it is clearly seen also in Figure 3.

3. DISCUSSION

The first interpretation of the observed periodic minimum in the LC of Nova Her 91 that comes to mind is that it is an eclipse of a light source, and the periodicity is the orbital period of the nova stellar system.

We now summarize a few major observational results that emerge from the time-resolved LC of the nova.

1. A local minimum identified in the LC of the nova from mid-April and on, appears periodically with the period P.
2. The width of the minimum of about 3 hr remained constant throughout the 12 weeks during which we observed the minima.
3. The structure of the minimum suggests that the eclipse of the light source is partial.
4. The depth of the minimum increased from about 0.1 mag in April, to more than 0.4 mag in July.

These facts are coupled to two other observational results emerging from Figure 1:

5. Between the time of our first detected minimum on April 13 and the last one on July 5, the star has faded by more than 3 mag.
6. At the same time, the $B-R$ color index became smaller, i.e., the star became *bluer* by about 0.8 mag.

A few important points of information about the evolution of the nova system in the early postoutburst stages can be inferred from these facts. We first note that the observed eclipse in April and May cannot be of the main light source of the system. Results (5) and (6) imply that the radius of the main light source must have decreased by at least a factor 5. A 10% eclipse in April (result [4]) would then become a total, or nearly total, eclipse in July, or no eclipse at all. From result (4) it is clear, however, that neither of these is the case. Result (2) tells us that the size of the eclipsed and of the eclipsing bodies did not change much during this period. We therefore conclude that the fading of the nova is due to a decline in the optical radiation of an uneclipsed light source. As a consequence, the fractional contribution of the eclipsed body to the total optical output of the system increases, hence the deepening of the observed minimum (result [4]).

From the same consideration one can also conclude that the fading light source cannot be the eclipsing body either. We therefore suggest that the eclipsed body in the system is a disk around the WD. It has been suggested that an accretion disk is indeed formed, or being restored, around the compact object in nova systems, after the expanding photosphere of the nova shrinks below the surface of the critical lobe of the WD (see, for example, Martin 1989 and references therein).

The absence of minimum on April 11 may imply that on that day there was no disk in the Nova Her 91 system. However, the large brightness of the main light source in the system, and the large flare which rose to maximum just half an hour before the expected time of the minimum (see Fig. 2), may well have masked a 0.05–0.1 mag deep minimum that actually had taken place at this date. If this is the case then according to our interpretation there was a disk in the system also on April 11. With the data at our hands, we are unable to decide between these two possibilities.

The size of an accretion disk and of a Roche lobe filling companion are determined mainly by the masses and by the basic dynamic parameters of the stellar binary system (Lubow & Shu 1975; Eggleton 1983). This explains the invariance of the width of the observed minimum during all our observing period (result [2]), on the face of rather dramatic thermal changes that the system was undergoing at the same time (results [5] and [6]).

Our interpretation is consistent also quantitatively with the commonly accepted model of a cataclysmic variable. Consider, for example, the data obtained on our last day of observations, July 5. The overall B magnitude of the system is 15.85, more than 10 mag fainter than the visual magnitude of the nova at maximum light (see § 1). About 60% of this luminosity is contributed by the disk, assuming that half of it is occulted at the bottom of the minimum observed in this day. From the

t_2–absolute magnitude relation given by Cohen (1985) we obtain that the absolute magnitude of Nova Her 91 at maximum light was -10. On July 5, the absolute magnitude of the disk was therefore about $+1$. This is a rather large brightness, if we take the absolute magnitude of novae at their quiescent state as typical values for the brightness of the disk (Warner 1987). We note, however, that there are quite a few novae on Warner's list with minimum luminosities in excess of this value.

Applying the same consideration to the data of April 13, we obtain that the disk on that date was more luminous than 12 weeks later. The decline in the disk luminosity may continue into the future, so the disk of Nova Her 91 may well eventually assume the characteristic luminosity of most of the old novae. A decline in the luminosity of the disk is indeed expected, since it is indirectly connected to the decline in the WD luminosity. The connection is through the influence of the primary luminosity on the secondary star, and on the mass-loss rate from it (Kovetz, Prialnik, & Shara, 1988).

The interpretation that we are proposing here, for the photometric behavior of Nova Her 91 in April–May–June, must stand a firm observational test in the near future. According to our model, from the second week of April and on, the WD is *not* eclipsed by the companion. For a symmetric disk around the WD this implies that no more than 50% of the surface area of the disk can be eclipsed. Thus, the depth of the minimum in the LC, measured in magnitude units, should not ever exceed the value 0.75.

Once the nova reaches the steady state of its luminosity, when the light contribution from the WD becomes negligible, one will be able to derive from the light curve the inclination angle and the size of the accretion disk and of the companion star of this binary system, and probably also to narrow down the range of possible values of other parameters that characterize this system. If spectroscopic observations succeed in providing radial velocity data, Nova Her 91 may well become a system with all or most of its binary elements known.

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