THE ASTROPHYSICAL JOURNAL, 182:L109–L112, 1973 June 15

OPTICAL STUDIES OF *UHURU* SOURCES. IV. THE LONG-TERM BEHAVIOR OF HZ HERCULIS = HERCULES X-1

C. A. JONES, W. FORMAN, AND W. LILLER
Harvard College Observatory, Cambridge, Massachusetts 02138
Received 1973 February 1, revised 1973 April 6

ABSTRACT

Harvard photographs of HZ Herculis taken during the period 1890–1972 reveal the following: (1) The orbital period has remained constant at 1.70017 days to within two parts in 10^5 since 1900. (2) HZ Her does not always display the 1.7-day light variation. (3) When the 1.7-day variation is not detectable, one observes a second brightness fluctuation with an amplitude of $\Delta m_{\rm pg} = 0.28 \pm 0.06$ and a period half that of the orbital motion.

Subject headings: variable stars — X-ray sources

I. INTRODUCTION

The numerous modes of variability at X-ray and optical frequencies of Hercules X-1 = HZ Herculis have been discussed by several authors (Tananbaum *et al.* 1972; Bahcall and Bahcall 1972; Davidsen *et al.* 1972; Forman, Jones, and Liller 1972). Using Harvard plates taken in the period 1890–1972, we have discovered two more modes of variability. The most conspicuous is a long-term turning off and on of the 1.7-day variability. The second mode of variation can be observed when the 1.7-day fluctuations cease; it is an amplitude variation of 0.28 ± 0.06 mag with a period half the orbital period of 1.7 days and with peak brightnesses coming whenever the X-ray star is 90° from eclipse. The obvious explanation is that we are seeing a distorted star in continuously changing aspects.

II. THE ORBITAL PERIOD OF HZ HERCULIS

Figure 1*a* shows the light curve of HZ Herculis derived from observations taken between 1945 and 1948 and folded with a period of 1.70017 days. Similar light curves were obtained for the intervals from 1890 and 1908 and during the late 1950s. These optical observations show a unique period of 1.70017 which has remained constant to within 2 parts in 10^5 since 1900 and agrees with the X-ray period (Tananbaum *et al.*).

III. THE LONG-TERM VARIABILITY

The curve in figure 1*a* closely resembles recent light curves for HZ Her (e.g., Bahcall and Bahcall 1972). However, commencing in 1949 and continuing until 1956 (fig. 1*b*), the variability ceases entirely in the sense that the system remains at or near minimum light during these years.

Harvard photographs taken since 1890 show that the OFF-ON behavior occurs sporadically as shown in figure 2, where we have plotted the magnitude of HZ Her near time of predicted maximum brightness (i.e., at phase $\phi = 0.5 \pm 0.2$) against date. The following properties of the long-term behavior of HZ Her can be derived from these observations:

1) The duration of an active or inactive state can be relatively brief. The shortest observed duration of an active mode is 402 days and the shortest observed inactive

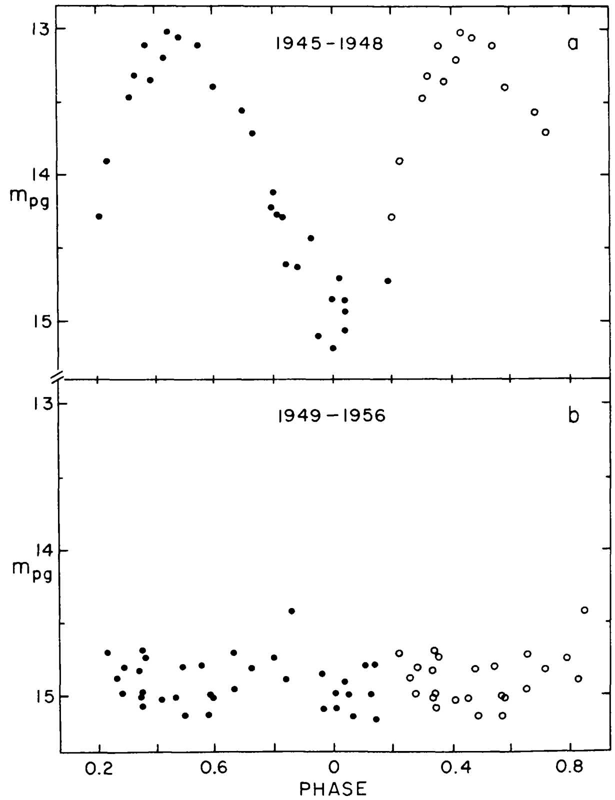

FIG. 1.—Light curves of HZ Her. (*a*) 1945–1948; (*b*) 1949–1956. All magnitudes were derived from iris photometer measurements made of blue-sensitive plates taken with the 41-cm refractor at Harvard's G. R. Agassiz Station. The one high point in (*b*) occurred in 1954. Open circles represent repeated points.

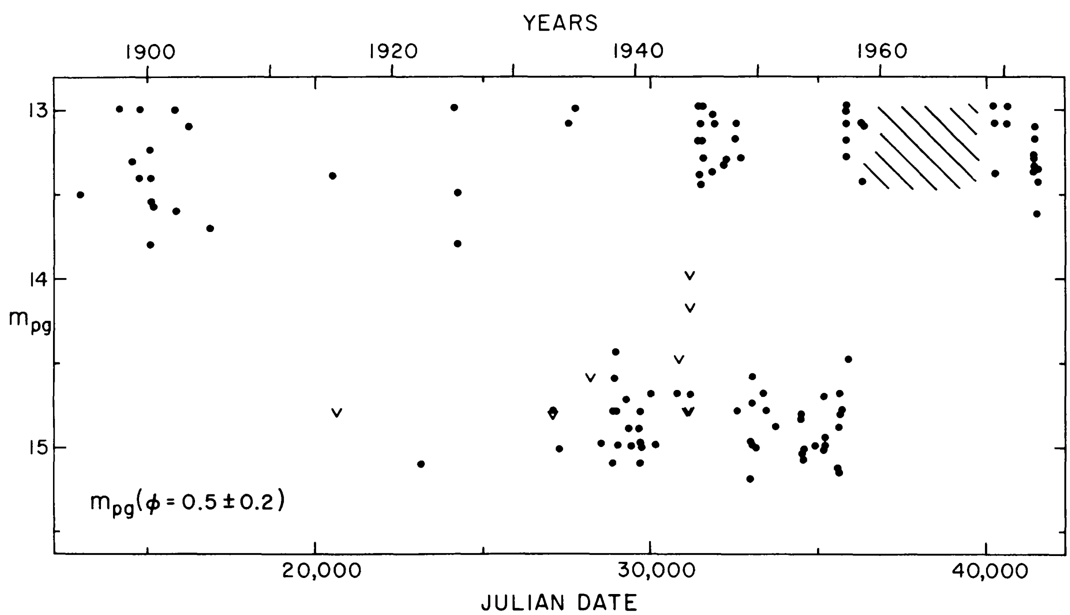

FIG. 2.—Long-term behavior of HZ Her. All plotted magnitudes occurred at phase $\phi = 0.5 \pm 0.2$, and therefore represent near-maximum brightnesses. Brightness upper limits are indicated by v's. The cross-hatching indicates the active behavior reported by Cherepaschuk *et al.*

period is less than 29 days. These two particular happenings occurred successively in 1948–1949.

2) The durations of the most extended active and inactive periods are difficult to determine because of occasional gaps in the data. However, it seems likely that HZ Her remained inactive for at least 7.2 years (from 1937 March to 1944 May). Combining our observations with those of Cherepashchuk, Luytiy, and Sunyaev (1973), we conclude that HZ Her has been active for the past 15 years.

3) No clear periodicity exists in the long-term behavior. However, between 1914 and 1957 there does appear to be a tendency for active states to occur every 10 to 12 years.

4) Since 1890, HZ Her has spent approximately half of its existence in an active mode and half in an inactive mode. No intermediate states have been observed.

An attractive and physically realistic mechanism that can produce such a behavior is an irregular or semi-irregular pulsation of the larger, optical star. When the star is in an expanded state, it completely fills or overfills its Roche lobe and feeds matter into the lobe surrounding the companion. The accretion of this matter onto the compact star produces the high-energy radiation that illuminates the face of the optical star. At other times when the star contracts to a size smaller than its Roche lobe, no mass exchange occurs, and the system enters the inactive state.

IV. THE ELLIPTICITY AND GRAVITY DARKENING EFFECTS

Averaging the magnitudes during the inactive phase from 1949 to 1956 (fig. 1*b*) into 10 equal groups, we obtained the light curve shown in figure 3. This light curve goes through two maxima occurring at approximately $\phi = 0.25$ and 0.75. While the data are not of sufficient quality to allow a precise determination of the period, they do eliminate the possibility of a constant value for the magnitude. The χ^2 for a constant value is 28 for 9 degrees of freedom, and the χ^2 for a sine curve of period half the orbital period is 5 for 7 degrees of freedom. For this best fit sine curve the peak-to-peak variation is 0.28 ± 0.06 mag.

If the optical star is a prolate spheroid with a uniform surface brightness and an orbital inclination of 90°, then the observed amplitude variation in the light curve implies that the ratio of the mass of the optical star to its companion is less than 0.1 (Kopal 1959). As Tananbaum *et al.* show, such a mass ratio is out of the question, and hence this effect cannot fully account for the observations. Gravity darkening would help to explain this amplitude variation because of reduced surface brightness at the

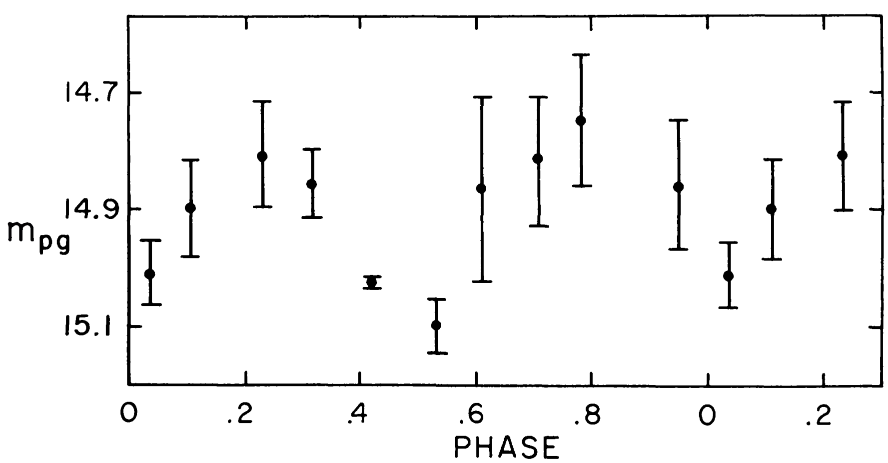

FIG. 3.—Averaged magnitudes from fig. 1*b*.

ends of the prolate spheroid (von Zeipel 1924). Further complications may result from rapid rotation of the star. Detailed calculations of these effects on the light curve may lead to estimates for the mass of the X-ray star.

Of the many people who have contributed their thoughts and comments on this work, we should like to single out Drs. R. Giacconi, E. Schreier, J. N. and N. A. Bahcall, A. P. Cowley, and J. B. Hutchings. Special thanks are due Dr. Harvey Tananbaum for a careful reading of the manuscript and many helpful suggestions.

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