Publications of the Astronomical Society of the Pacific, **112**:840–845, 2000 June

Long-Term *VRI* Photometry of 89 (V441) Herculis

John R. Percy and Akos G. Bakos
Erindale Campus, and Department of Astronomy, University of Toronto, Mississauga, ON L5L 1C6, Canada; jpercy@erin.utoronto.ca

and

Gregory W. Henry
Center of Excellence in Information Systems, Tennessee State University, Nashville, TN 37203-3401; henry@schwab.tsuniv.edu

Received 2000 February 3; accepted 2000 March 17

ABSTRACT. We report 4500 days of *VRI* photometry of the peculiar high-latitude F2 Ibe star 89 (V441) Herculis, from a robotic photometric telescope, and the American Association of Variable Star Observers photoelectric photometry program. We detected the previously known photometric period of 65.2 days and also the 283 day period which was previously observed in radial velocity only and ascribed to binarity. We have determined the relative amplitudes and phases of light, color, and radial velocity for each period. The 65.2 day period appears to be due to pulsation—probably radial. The nature of the 283 day variations is unclear; we discuss possible origins, based on models of the system. We have determined times of maxima from our data and constructed the best available $O-C$ diagram; it suggests that the 65.2 day period is increasing on a timescale of a few hundred years.

1. INTRODUCTION

V441 (89) Herculis (=HR 6685 = HD 163506, $V = 5.46$, SpT F2 Ibe [*Bright Star Catalogue*; Hoffleit 1982]; SRd, $V = 5.34$–5.48, period = 70? days [*General Catalogue of Variable Stars*; Kholopov 1985]) is a bright member of the UU Herculis stars (Sasselov 1981)—high-latitude yellow supergiants with unstable light curves. These stars were initially of interest because it was not clear whether they were young, high-mass supergiants which had somehow reached a large distance from the Galactic plane or whether they were old, low-mass stars which were masquerading as young supergiants. The latter appears to be the case. The star is a well-studied infrared source, which is consistent with its being a post–asymptotic-giant-branch (AGB) star which has undergone mass loss. See the various papers in Sasselov (1993) for an extensive discussion of high-latitude supergiants, especially the paper by Fernie (1993).

The variability of 89 Her was first noted by Worley (1956) and has been studied especially by Fernie (1981, 1983, 1986, 1989, 1990, 1991) and Fernie & Seager (1993). The star varies in brightness and radial velocity with a period of about 65 days and with irregular amplitude. In particular, the radial velocity variations were sometimes detectable (Burki, Mayor, & Rufener 1980, Fig. 3; Arellano Ferro 1984, Fig. 2) but sometimes almost absent; Fernie (1981) found only small irregular variations on a timescale of weeks. Previous automatic photometric telescope *VRI* photometry of 89 Her has been presented by Donahue et al. (1993).

In 1984, Arellano Ferro (1984) announced that the radial velocity of this star varied with a period of about 285 days, and he ascribed this to binary motion. The radial velocity had also been measured by Burki et al. (1980). Waters et al. (1993) determined a period of 288.4 days and derived other orbital elements, assuming that the velocity variations were due to binarity. The elements included $e = 0.19 \pm 0.07$, $2K = 6.2$ km s^{-1}, and $f(M) = 0.00084\ M_\odot$. If the variable has a mass of 0.6 $M_\odot$, then the mass of the secondary is $\geq 0.073\ M_\odot$. They also proposed a model of both the 89 Her system and the circumstellar envelope in which the system orbits within a cavity in the envelope. Mastrodemos & Morris (1998) have studied the formation of accretion disks in binary systems like 89 Her.

The historical light, color, and velocity variations of 89 Her have been discussed in many of the papers listed above. Fernie maintains a Web site[1] which contains references to his published data, as well as a link to unpublished data which others are welcome to use as long as they reference the site.

2. DATA AND METHODS

Our photometric data come from two sources. We acquired 2448 differential group observations through

[1] http://ddo.astro.utoronto.ca/89her.html.

Johnson *VRI* filters between 1986 and 1999 with the Fairborn-10 0.25 m automatic photoelectric telescope (APT) located at Fairborn Observatory in southern Arizona. This telescope uses an uncooled photodiode detector to make group observations in the sequence K, sky, C, V, C, V, C, V, C, sky, K, where K is the check star 86 μ Her (= HR 6623 = HD 161797, G5 IV), C is the comparison star 87 Her (= HR 6644 = HD 162211, K2 III), and V is 89 Her. Three V − C and two K − C differential magnitudes are calculated and averaged together to create group means. These group means are then corrected for differential extinction (determined nightly since 1995), transformed to the Johnson system with yearly mean transformation coefficients, and treated as single observations thereafter. External precision of the group means, based on standard deviations for pairs of constant stars, averages 0.010 mag on good nights. Since the APT is programmed to acquire data anytime it can find stars, observations taken in nonphotometric conditions are automatically removed from the data set if the standard deviation of the group-mean differential magnitude exceeds 0.02 mag. The few poor observations that escape this "cloud-filtering" process are removed by inspection of the light curves. The first 2 years of observations are poorly calibrated and tend to show an offset relative to the rest of the data. Therefore, we use these early data only for determining times of maximum and minimum brightness. Finally, the check minus comparison star differential magnitudes demonstrate that both 86 Her and 87 Her are constant to 0.014 mag (but see below). Further details on the APT and its operation can be found in Henry (1995a, 1995b) and on the Web.[2]

Additional Johnson V data were obtained from the American Association of Variable Star Observers (AAVSO) photoelectric photometry program (Landis, Mattei, & Percy 1992; H. J. Landis 1999, observations from the AAVSO photoelectric photometry archive). The data are also differential and are corrected for differential extinction and transformed to the Johnson system using the catalog $B-V$ color of the star, assuming it to be constant. The precision of the data is typically 0.01 mag. Prior to JD 2,448,150, HR 6754 (F0 V, $V = 6.373$) was used as a comparison star. This star turned out to be a low-amplitude variable star, so it was replaced by 87 Her (which is also slightly variable; see below). The AAVSO observations, prior to JD 2,448,150, have been converted to V magnitudes by use of the check star HR 6697 (G0 V, $V = 6.305$). The observers, and the number of observations which they contributed, are as follows: Paul Beckman (7), Ted Beresky (73), Frank Dempsey (14), Robert Johnsson (2), Paul Kneipp (2), Kenneth Luedeke (65), Howard Landis (7), Thomas Langhans (4), Frank Mellilo (8), Phil Manker (40), Donald Pray (54), Lee Snyder (1), Nick Stoikidis (5), Raymond Thompson (125), David B. Williams (4), and Jim Wood (101).[3]

Slight variability in 87 Her was first discovered by Skiff (Lockwood & Skiff 1988) and was subsequently discussed by Fernie (1991, 1993). The most noticeable variability coincides with the first 2 years of the APT data, when the calibration was uncertain; it does not affect the analysis or conclusions in the present paper.

The two V data sets were merged for period analysis. Note that the AAVSO measurements fill the gaps in the APT measurements, which occur during the Arizona monsoon season. Power spectrum analysis was carried out with the AAVSO program TS[4] and the program Period98 (Sperl 1998). For comparison with the light and color curves, radial velocities were taken from the following sources: Burki et al. (1980), Fernie (1981), and Arellano Ferro (1984, 1985).

3. RESULTS

3.1. Light and Color Curves

The merged V light curve (Fig. 1) showed an average magnitude of 5.45 and a range of 5.33–5.58. There were no obvious long-term variations, other than an apparent slow decrease in the amplitude after JD 2,450,000. In fact, the character of the light curve seems to change somewhat after JD 2,450,000, with the 65.2 day period becoming less prominent (see § 3.3). The $V-R$ color ranges from 0.29 to 0.40,

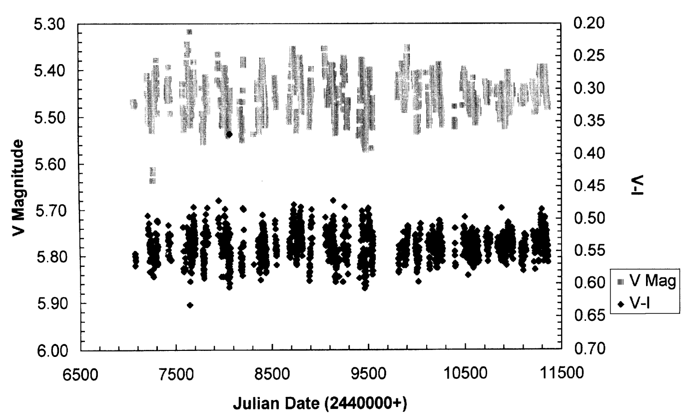

FIG. 1.—Revised combined data (APT 2,447,000+). V-magnitude and $V-I$ color curves for 89 Her, using all available data.

[2] See http://schwab.tsuniv.edu. The APT data are available on this same site.

[3] The AAVSO photometry can be obtained by contacting the Director, AAVSO, 25 Birch Street, Cambridge, MA 02138-1205, USA; aavso@aavso.org.

[4] http://www.aavso.org.

with a mean of 0.345. The $V-I$ color (Fig. 1) ranges from 0.47 to 0.60, with a mean of 0.535.

3.2. Times of Maximum and Minimum Brightness

The following Julian Dates (less 2,440,000) of maximum and minimum were determined graphically, from the V light curve. Maxima: 7302, 7625, 7757, 7954, 8019, 8153, 8406, 8725, 8786, 8850, 9130, 9185, 9258, 9435, 9500, 9917, 10167, 10234, 10584, 10632, 10712, 10888, 10947, 11283, 11332; minima: 7267, 7594, 7662, 7792, 7985, 8046, 8184, 8372, 8439, 8754, 8883, 9087, 9156, 9215, 9283, 9467, 9536, 9877, 10010, 10135, 10205, 10262, 10513, 10554, 10610, 10917, 10972, 11311.

3.3. Period Analysis of the Light Curves

The power spectrum of the merged V light curves (Fig. 2) shows two periods: 65.08 and 282.4 days. There are also two weaker "alias" peaks at frequencies which are 1 cycle per year lower than these. There are some even weaker peaks which we believe are connected with the irregularity of the 65 day variation; they are different in the power spectrum of the light curve before JD 2,450,000 and the light curve after (see below). The periods obtained from the other light and color curves are, for the R curve, 65.13 and 281.2 days; for the I curve, 65.13 and 281.2 days; for the $V-I$ curve, 65.13 and 276.8 days. These values were obtained with the AAVSO TS program. The value of the short period obtained for the merged V curve with the Period98 program was 65.16 days, which is entirely consistent with the above result, as expected.

Because the light curve after JD 2,450,000 seemed to be different from the light curve before, we determined the power spectrum of this later portion of the light curve. There were a series of peaks at 60–70 days and a broad peak at 250–300 days. For completeness, we calculated the power spectrum of the light curve prior to JD 2,450,000. It was very similar to Figure 2 (peaks at 65.08 and 282.4 days and the two alias peaks mentioned above), except that the relative height of the peak at 65.08 days was slightly higher.

The value of the short period is similar to that obtained by previous observers. The value of the long period is comparable with the periods (283 and 288 days) obtained by Arellano Ferro (1984) and by Waelkens & Mayor (1993) for the radial velocity variations. We determined the power spectrum of the Burki et al. (1980) radial velocities; it showed weak peaks at periods of 50–60 days and a stronger peak at a period of 250–300 days. Donahue et al. (1993) found no evidence for the 283 day period in their V photometry.

As a check on a "constant" star, we determined the power spectrum of the APT (check star minus comparison star) V photometry. The power spectrum contained about a dozen peaks, of similar height, at periods between 100 and 1000 days. The 65.2 day period produced a V phase diagram with an amplitude of 0.007 mag; the 283 day period produced a V phase diagram with an amplitude of 0.010 mag; a period of 300.5 days (the highest peak in the power spectrum) produced a V phase diagram with an amplitude of 0.012 mag. We conclude that the comparison and check stars are constant in brightness.

3.4. Light and Color Curves: Amplitude and Phase Relations

The V and $V-I$ phase curves are shown in Figures 3 (period 65.2 days) and 4 (period 283 days). In each case, the $V-I$ curve seems to lead the V curve, but only by 0.05 cycle at the most. The ratio $\Delta(V-I)/\Delta V$ is 0.50 for the 65.2 day period and 0.38 for the 283 day period. Since these ratios

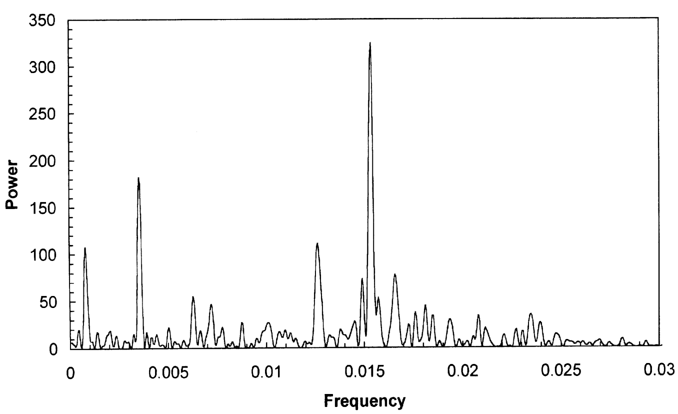

FIG. 2.—Power spectrum of the combined and revised V-magnitude data, showing peaks at 65.2 days (0.0153 cycle day^{-1}) and 283 days (0.00353 cycle day^{-1}).

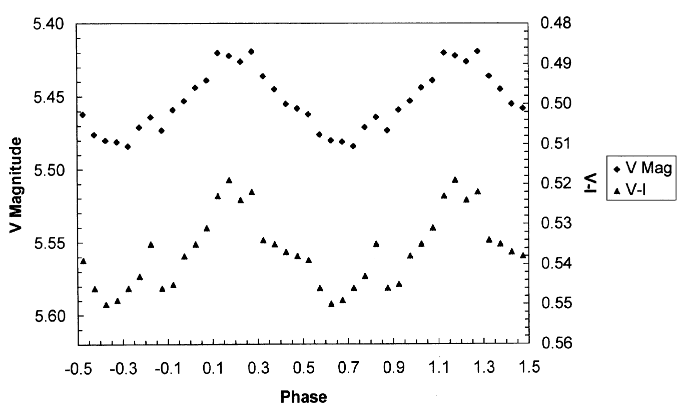

FIG. 3.—V-magnitude and $V-I$ color phase curves, using a period of 65.2 days and an epoch of JD 2,446,500.

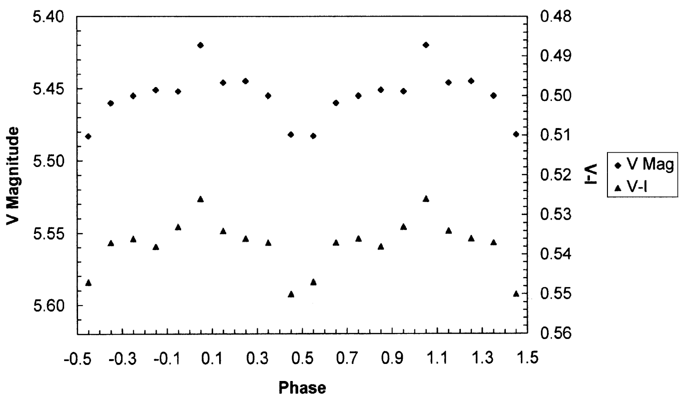

FIG. 4.—V-magnitude and $V-I$ color phase curves, using a period of 283 days and an epoch of JD 2,446,500.

depend slightly on the number of bins in the phase curves, the difference between the ratios is only marginally significant.

3.5. Light and Velocity Curves: Amplitude and Phase Relations

The V and V_r phase curves are shown in Figures 5 (period 65.2 days) and 6 (period 283 days). In each case, the V_r curve leads the V curve by 0.10–0.15 cycle. The ratio $\Delta V_r/\Delta V$ is 97 km s^{-1} mag^{-1} for the 65.2 day period, using the Burki et al. (1980) data, and 85 km s^{-1} mag^{-1} for the 283 day period. The ratios are slightly different when all the radial velocity data are used, but we prefer to use the more homogeneous Burki et al. (1980) data.

Waters et al. (1993) have published more recent radial velocity data on 89 Her. The data are not well distributed in phase, but a power spectrum of this data shows a broad peak at 60–70 days, as well as at a longer period. A phase curve using the more recent radial velocity data of Waters

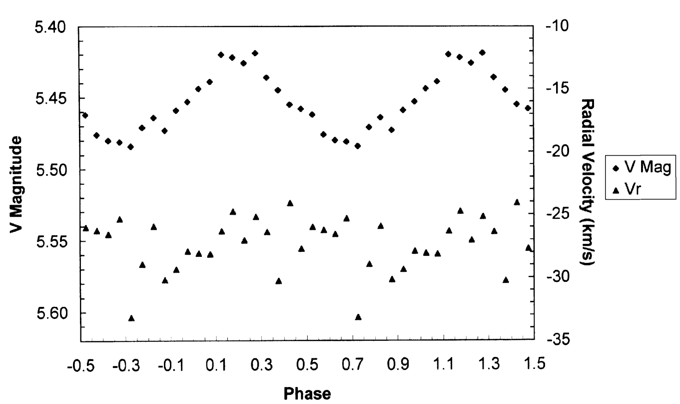

FIG. 5.—V-magnitude and radial velocity (Burki et al. 1980) phase curves, using a period of 65.2 days and an epoch of JD 2,446,500.

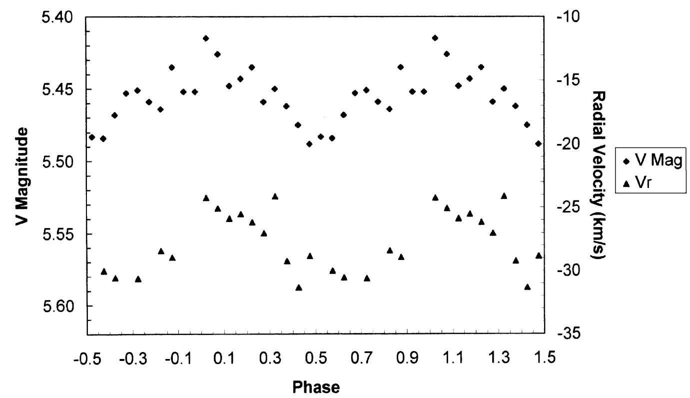

FIG. 6.—V-magnitude and radial velocity (Burki et al. 1980) phase curves, using a period of 283 days and an epoch of JD 2,446,500.

et al. (1993) and the 65.2 day period, and the same epoch as in Figure 5, has the same amplitude (3–5 km s^{-1}); the phase of maximum is not well defined, but it is not inconsistent with Figure 5.

3.6. Random and Systematic Period Changes

Times of maximum and/or minimum brightness were taken from the following sources: Fernie (1986), Bakos (1987), and Fernie (1989) and from § 3.2.

These were first tested for random cycle-to-cycle period fluctuations. Such fluctuations have been found in Mira stars (Eddington & Plakidis 1929; Percy & Colivas 1999), RV Tauri stars (Percy et al. 1997), the Population II Cepheid RU Cam (Percy & Hale 1998), and at least two Population I Cepheids (J. R. Percy & L. Nelson 2000, in preparation). The formalism of Eddington & Plakidis (1929) was used: if $\langle u(x) \rangle$ is the mean absolute difference between $O-C$ values which are x cycles apart, then $\langle u(x) \rangle^2 = 2a^2 + \epsilon^2 x$, where a is the mean observational error in measuring the time of maximum or minimum and ϵ is the mean fluctuation in period in days, per cycle. The data were sparse, but the behavior of $\langle u(x) \rangle^2$, from $x = 1$ to 10, was not linear. There is therefore no evidence for random, cycle-to-cycle period fluctuations in this star.

Figure 7 shows the "best" $O-C$ diagram for 89 Her, using all available times of maximum after JD 2,443,000. Before this date, the data are too fragmentary; there are large gaps between some of the data, and the cycle numbers are therefore uncertain.

In Figure 7, there is a slight ambiguity in the cycle number in the gaps at JD 2,443,500 and 2,446,200, but the cycle numbers in Figure 7 provide the smoothest parabolic fit to the data. The average deviation in Figure 7 is ± 8.0 days. If the first three points are moved down 1 cycle, the average deviation is ± 9.2 days, and there are many more

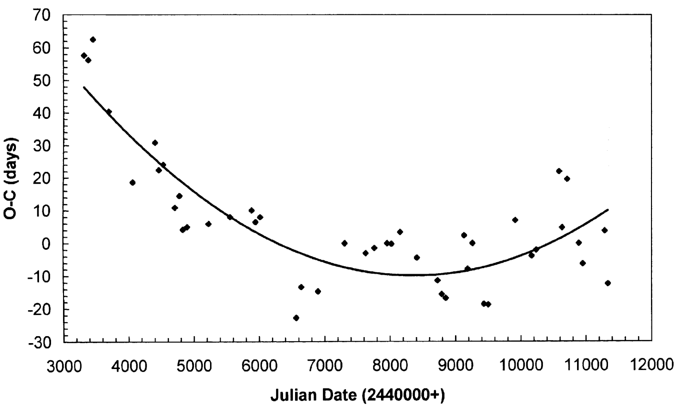

FIG. 7.—The preferred $O-C$ diagram for 89 Her, using a period of 65.2 days and an epoch of JD 2,447,302. The equation of the best-fit parabola is $y = (2.267 \times 10^{-6})x^2 - (3.793 \times 10^{-2})x + 148.8$; y or $O-C$ is in days, and x is the time in days elapsed since JD 2,440,000.

extreme deviations. If the points after JD 2,446,500 are moved up 1 cycle, then the average deviation is increased to ± 11.1 or 14.1 days, depending on how the first three points are dealt with; in either case, there are many more extreme deviations. The equation of the best-fit parabola is

$$O-C = (2.267 \times 10^{-6})E^2 - (3.793 \times 10^{-2})E + 148.8 .$$

In this equation, E is the time in days elapsed since JD 2,440,000 and $O-C$ is expressed in days. The characteristic time for the period to change, $P/\dot{P}$, is about 600 years. The period is increasing.

4. DISCUSSION AND CONCLUSIONS

The 65.2 day variations are assumed to be due to pulsation. The period is consistent with those of other low-mass yellow supergiants such as luminous Population II Cepheids, RV Tauri stars, and SRd variables. The low amplitude and irregular variability are consistent with the behavior of other UU Herculis stars. It should be stressed that irregularity is not confined to UU Herculis stars; it is found in SRd variables, including Population I hypergiants such as ρ Cas.

The pulsation mode can potentially be determined from the observed pulsation constant Q. If the mass is 0.6 $M_{\odot}$ and the radius is 43 $R_{\odot}$ (using Waters et al.'s [1993] preferred effective temperature), then the pulsation constant Q is 0.179. The theoretical (nonlinear, nonadiabatic) Q-value for the radial fundamental mode of a model RV Tauri star with the same mass and luminosity as 89 Her, but a slightly cooler temperature, is 0.134 (Fokin 1994, Table 1). This suggests that the short period is close to the radial fundamental period.

Nonradial pulsation has already been proposed for 89 Her on the basis of its irregular light and velocity variations (Waelkens & Mayor 1993) and on the basis of the low $2K/\Delta m$ ratio (Fernie 1993). The $2K/\Delta m$ ratio which we derive in § 3.5, however, is not unusual for radial pulsation. We emphasize that the 65.2 day period in the 89 Her radial velocity data has now been found by several groups including Waters et al. (1993), though it is of low and irregular amplitude.

We have detected light and color variations with the 283 day period for the first time; they were not detected by Donahue et al. (1993). Our 283 day period is not significantly different from the 288 day period derived by Waters et al. (1993) from the radial velocities. The cause of the long-term light and color variations is not clear. The relative amplitudes and phases of light, color, and velocity are similar for the 65.2 and 283 day periods, so they could both be pulsation periods. The longer period would have to be a nonradial mode, since the short period is close to the radial fundamental period (see above).

On the other hand, long-term light, color, and velocity variations are found in RVb stars (RV Tauri stars with long-term variations in mean light), and these are thought to be due to binarity (Percy 1993; Fokin 1994). If the variable star is orbiting within a cavity in the circumstellar envelope (Waters et al. 1993), then it might be possible to produce the phase curves shown in Figures 4 and 6, though it is curious that the phase curves for such extinction-related variability are so similar to the phase curves for the pulsation-related variability. Further modeling of the long period should be a priority.

The $O-C$ diagram for 89 Her, if interpreted as being due to smooth evolutionary changes, suggests an *increase* in period, and hence in radius, on a timescale of a few hundred years. UU Herculis stars are thought to be *decreasing* in period on that timescale, as they contract from the AGB to the white dwarf stage. It is possible that we have made an incorrect assignment of cycle numbers in our $O-C$ diagram or that we have observed an apparently parabolic $O-C$ diagram as a result of the effect of random cycle-to-cycle period fluctuations. The former is unlikely, as mentioned in § 3.6, and the application of the Eddington & Plakidis (1929) formalism did not support the latter explanation. We conclude that 89 Her is currently evolving from blue to red on the H-R diagram. It is important to continue to monitor this star as continuously as possible, to see whether the apparent increase in period continues.

We are grateful to Lou Boyd at Fairborn Observatory for his continuing operation of the Fairborn-10 APT. Astronomy with automated telescopes at Tennessee State University has been supported by the National Aeronautics and Space Administration, most recently through NASA grants NCC5-96 and NCC5-228, which funds TSU's Center for Automated Space Science, and the National Science Foundation, most recently through NSF grant HRD-9706268, which funds TSU's Center for Systems Science Research.

Akos G. Bakos was a participant in the Summer Career Placement Program of the Government of Canada. We thank the AAVSO photoelectric observers, and the archivist Howard J. Landis, for their essential role in this project and Don Fernie and an anonymous referee for helpful comments. John Percy acknowledges, with thanks, a research grant from the Natural Sciences and Engineering Research Council of Canada. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Arellano Ferro, A. 1984, PASP, 96, 641
———. 1985, MNRAS, 216, 571
Bakos, G. A. 1987, Commun. Konkoly Obs., 90, 111
Burki, G., Mayor, M., & Rufener, F. 1980, A&AS, 42, 383
Donahue, R. A., Rao, L. M., Baliunas, S. L., & Dupree, A. K. 1993, in ASP Conf. Ser. 45, Luminous High-Latitude Stars, ed. D. D. Sasselov (San Francisco: ASP), 285
Eddington, A. S., & Plakidis, S. 1929, MNRAS, 90, 65
Fernie, J. D. 1981, ApJ, 243, 576
———. 1983, ApJ, 265, 999
———. 1986, ApJ, 306, 642
———. 1989, PASP, 101, 171
———. 1990, PASP, 102, 442
———. 1991, PASP, 103, 1087
———. 1993, in ASP Conf. Ser. 45, Luminous High-Latitude Stars, ed. D. D. Sasselov (San Francisco: ASP), 253
Fernie, J. D., & Seager, S. 1993, PASP, 105, 751
Fokin, A. B. 1994, A&A, 292, 133
Henry, G. W. 1995a, in ASP Conf. Ser. 79, Robotic Telescopes: Current Capabilities, Present Developments, and Future Prospects for Automated Astronomy, ed. G. W. Henry & J. A. Eaton (San Francisco: ASP), 37
———. 1995b, in ASP Conf. Ser. 79, Robotic Telescopes: Current Capabilities, Present Developments, and Future Prospects for Automated Astronomy, ed. G. W. Henry & J. A. Eaton (San Francisco: ASP), 44
Hoffleit, D. 1982, The Bright Star Catalogue (New Haven: Yale Univ. Obs.)
Kholopov, P. N. 1985, General Catalogue of Variable Stars (4th ed.; Moscow: Nauka)
Landis, H. J., Mattei, J. A., & Percy, J. R. 1992, Inf. Bull. Variable Stars, 3739, 1
Lockwood, G. W., & Skiff, B. A. 1988, Air Force Geophys. Lab. Tech. Rep. (AFGL-TR-88-0021)
Mastrodemos, N., & Morris, M. 1998, ApJ, 497, 303
Percy, J. R. 1993, in ASP Conf. Ser. 45, Luminous High-Latitude Stars, ed. D. D. Sasselov (San Francisco: ASP), 295
Percy, J. R., Bezuhly, M., Milanowski, M., & Zsoldos, E. 1997, PASP, 109, 264
Percy, J. R., & Colivas, T. 1999, PASP, 111, 94
Percy, J. R., & Hale, J. 1998, PASP, 110, 1428
Sasselov, D. D. 1981, Astron. Tsirk., 1167, 6
Sasselov, D. D., ed. 1993, ASP Conf. Ser. 45, Luminous High-Latitude Stars (San Francisco: ASP)
Sperl, M. 1998, Commun. Asteroseismology, 112, 1
Waelkens, C., & Mayor, M. 1993, in ASP Conf. Ser. 45, Luminous High-Latitude Stars, ed. D. D. Sasselov (San Francisco: ASP), 318
Waters, L. B. F. M., Waelkens, C., Mayor, M., & Trams, N. R. 1993, A&A, 269, 242
Worley, C. E. 1956, PASP, 68, 62