THE ASTROPHYSICAL JOURNAL, 294:207–215, 1985 July 1

THE OLD GALACTIC CLUSTER NGC 188 AND THE ORIGIN OF THE W URSAE MAJORIS–TYPE CONTACT BINARIES[1]

SALLIE L. BALIUNAS
Harvard-Smithsonian Center for Astrophysics
AND
EDWARD F. GUINAN
Villanova University
Received 1984 September 4; accepted 1985 January 16

ABSTRACT

Spectroscopic observations of the four faint, short-period light variables EP Cep, EQ Cep, ER Cep, and ES Cep confirm that they are W UMa–type, or contact, binaries. The binaries ER Cep and ES Cep are members of the old open cluster NGC 188 (age ~5–10 × 10^9 yr) by a radial-velocity criterion; all four are associated with the cluster by their position in space and in its color-magnitude diagram. Combined with the light curves of the variables, our inferred component radial velocities reveal spectroscopic mass ratios that characterize these binaries as "W-type" systems that are physically similar to those in the field. The high spatial incidence of these systems in a cluster of such great age suggests that these stars have evolved into the contact configuration from detached or semidetached progenitors that lose orbital angular momentum, perhaps through magnetic braking in stellar winds. The W UMa–type binaries may coalesce and form the rapidly rotating yellow giants, the FK Comae stars.

Subject headings: clusters: open — stars: evolution — stars: W Ursae Majoris

I. INTRODUCTION

The W Ursae Majoris–type contact binary systems are the most common binary known, with a space density of ~10^{-4} of all stars (Budding 1982). These are binaries whose orbital periods are generally shorter than ~$0^{\rm d}.7$ and whose components are in contact with their Roche limiting surfaces (Kopal 1955; Lucy 1968; Binnendijk 1970). Light variations arise from the mutual eclipses and from the highly distorted figures of the stars caused by tidal interaction and rotational flattening. The component stars of W UMa systems are generally in the range of F–K spectral types and lie near or just above the main sequence. Their rapid rotation produces ultraviolet and X-ray chromospheric and coronal emission that is among the brightest in surface flux of cool stars (Eaton 1983; Rucinski and Vilhu 1983; Cruddace and Dupree 1984). The total mass of a typical W UMa–type binary is less than ~2.5 $M_\odot$, and while the spectral types of the components are similar, the masses of the components are quite dissimilar. In some W UMa–type systems, component mass ratios as small as ~0.1 have been reported (cf. Binnendijk 1970; Mochnacki 1981).

The origin and evolutionary status of the W UMa systems are controversial topics (see Hazelhurst 1970 and Mochnacki 1981 for discussions). Broadly, theoretical investigations of these stars' origin and evolution are distinguished by the conservation of angular momentum or loss of it. Models with constant angular momentum require that the stars appear on the zero-age main sequence in close proximity. Their structure is described by either the thermal relaxation oscillation (TRO) theory (Lucy 1976, 1977) or the contact discontinuity (DSC) theory (Shu, Lubow, and Anderson 1976, 1979). For models in which angular momentum is lost the systems evolve into the contact configuration (cf. Huang 1966; van't Veer 1979; Vilhu and Rahunen 1980). The question of the ages of the W UMa–type binaries is, therefore, a crucial one for understanding them.

With an age determined from its color-magnitude diagram between 5 and 10 × 10^9 yr, NGC 188 is one of the oldest galactic clusters known (Sandage 1962; Janes and Demarque 1983; VandenBerg 1983). Not only its great age but also its stellar content make this cluster remarkable. There are four variable stars with periods of about 7–8 hr in this cluster that are presumed to be W UMa binary systems, EP, EQ, ER, and ES Cep (Hoffmeister 1964; Efremov *et al.* 1964; Worden *et al.* 1978). These variables are assumed to be cluster members on the basis of their position in the color-magnitude diagram of the cluster and their spatial coincidence with the cluster in the sky (Efremov *et al.* 1964). If indeed they are cluster members and W UMa–type binaries, these variables likely are coeval with the cluster and hence extremely old. A puzzling feature of the cluster is that the local space density inferred from the presence of four W UMa–type binaries in NGC 188 is about 20–50 times greater than in the field or in any other known cluster.

Because of the faintness of these stars [m_V(max) between +15.5 and 16.6 mag] and the need to obtain relatively short exposures so that the orbital motions will not smear the velocities in the spectra, it is necessary to use a large-aperture telescope (such as the MMT) and an efficient spectroscope-detector system to obtain useful spectra. For these reasons these stars have not been observed before and the spectra presented here apparently are the first obtained of these variables. In addition, the analysis using cross-correlation techniques permits the radial velocities of the component stars to be extracted, probably making these binaries the faintest systems for which this has been accomplished so far. This paper describes the initial spectroscopic study of these short-period variables in NGC 188. Preliminary reports of this study have been given by Baliunas and Guinan (1983, 1984).

[1] Research reported here used the Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

TABLE 1

SPECTROSCOPIC OBSERVATIONS OF THE W URSA MAJORIS–TYPE SYSTEMS IN NGC 188

Star	Sequence No.	Midexposure HJD[a] (2,445,500+)	Phase[b]	Radial Velocity[c] (km s^{-1}) Hot Star ($V_h - V_0$)	Cool Star ($V_c - V_0$)	Number of Templates
ER Cep	ZD 3100	29.7709	0.62	+7(±10)		6
	ZD 3102	29.8189	0.79	+219(±13)	−144(±32)	5
	ZD 3104	29.8675	0.96	[+114(±34)	−124(±23)][d]	4
EQ Cep	ZD 3099	29.7445	0.78	+143(±16)	−56(±3)	4
	ZD 3105	29.8932	0.26	−211(±24)	+90(±17)	3
ES Cep	ZD 3091	27.9163	0.52	−17(±8)		5
	ZD 3098	29.7195	0.78	+222(±18)	−25(±8)	6
	ZD 3103	29.8432	0.15	+13(±8)		5
EP Cep	ZD 3101	29.7959	0.22	−123(±60)	+24(±16)	4

[a] Heliocentric Julian Date during middle of 30 minute exposure.

[b] Fractional phases were calculated from the following ephemerides: EP Cep: 2,439,236.472 + 0^{d}289745E, Kholopov and Sharov 1967*b*; EQ Cep: 2,439,237.319 + 0^{d}306906E, Kholopov and Sharov 1967*c*; ES Cep: 2,440,808.380 + 0^{d}342454E, Kholopov and Sharov 1967*a*; ER Cep: 2,441,975.043 + 0^{d}2857355E, Worden *et al.* 1978. Radial velocity crossing and geometric eclipse occur at phases 0.0 and 0.5; maximum velocity separation and light occur at phases 0.25 and 0.75.

[c] ($V_h - V_0$) and ($V_c - V_0$) are the radial velocity displacements relative to the assumed center of mass of the binary for the hotter and cooler components respectively. When only one velocity is listed, the component spectra are unresolved.

[d] Stellar orbital velocities at this phase are biased by the Rossiter effect. See text.

II. OBSERVATIONS

Spectra of the four variables in NGC 188 were obtained in 1983 July with the Multiple Mirror Telescope (MMT), and the details of the observations are listed in Table 1. The dual-slit spectrograph uses an 832 lines mm^{-1} grating in second order and produces spectra with a resolution of about 1.2 Å at λ4000. Spectra are recorded with two photon-counting, intensified Reticon arrays (Latham 1982). In this double-slit configuration the background correction is recorded simultaneously with the stellar spectrum. Sensitivity variations present on a relatively small spatial scale in the instrumental response are removed with a flat field generated from the spectrum of an incandescent source. Wavelength calibrations were obtained from emission lines present in an He-Ne-Ar arc spectrum (cf. Tony and Davis 1979). The wavelength solutions were monitored before and after each stellar exposure. Two 15 minute stellar exposures are summed for each final spectrum analyzed.

These variables are faint, reaching a maximum apparent V magnitude of only about +15.5 mag. Thus, sequential pairs of spectra must be summed because the individual 15 minute exposures contain too few counts to produce significant cross-correlation peaks in our analysis. The total integration time of 30 minutes in the summed spectra smears the radial velocity phases by about 6%.

III. ANALYSIS

The radial velocities of the variables were determined with cross-correlation techniques. The four variables were sampled at different phases during the two nights of observations (Table 1). Cross correlations were calculated from several different stellar spectra used as templates for measuring the radial velocities of the variables (Table 2). Spectra of the stars I-32 and I-33, presumably cluster members, were chosen as primary templates because their spectrum features are sharp and match well those of the variable stars' spectra. These two templates were observed on 1983 July 13/14, the night most of the variables were monitored. It was not known *a priori* whether or not the stars I-32 and I-33 were cluster members or were themselves spectroscopic binaries. Two other stars, I-10 and I-91 in NGC 188, observed in 1984 May (G. Smith, private communication), were adopted as templates as well. Together with the giant stars T829 in M67 (Janes and Smith 1984) and AV in M3 (Norris and Smith 1984), these six spectra served as primary templates for radial-velocity determinations of the variables. Four other stars in NGC 188, I-76, I-97, I-101, and I-104 (G. Smith, private communication) were used as secondary templates to calibrate the velocity of the cluster and to search for spectrum peculiarities of the primary templates. The spectrum of I-32 in NGC 188 and its autocorrelation are shown in Figure 1.

The cross- and autocorrelations are calculated as described by Tonry and Davis (1979). These correlations are calculated using fast Fourier transforms of apodized spectra binned into linear logarithmic wavelength scales. This kind of numerical cross-correlation technique has been successful in the measurement of radial-velocity curves of W UMa–type binaries in the field (McLean 1981, 1983; McLean and Hilditch 1983; Hrivnak *et al.* 1984).

TABLE 2

TEMPLATE STARS FOR RADIAL VELOCITY MEASUREMENTS

Cluster	Star	V^a	$(B-V)_0{}^a$
Primary Templates:			
NGC 188	I-32	+14.4	+0.57
NGC 188	I-32	14.5	0.69
M67	T829	9.5	1.26
M3	AV	14.0	0.98
NGC 188	I-10	14.9	0.69
NGC 188	I-91	14.8	0.64
Secondary Templates:			
NGC 188	I-76	+14.9	+0.61
NGC 188	I-97	15.0	0.90
NGC 188	I-101	15.0	0.61
NGC 188	I-104	15.4	0.62

[a] References for NGC 188: photometry, Eggen and Sandage 1969; reddening, Twarog 1978. For M67: Murray and Clements 1968. For M3: Sandage and Katem 1982.

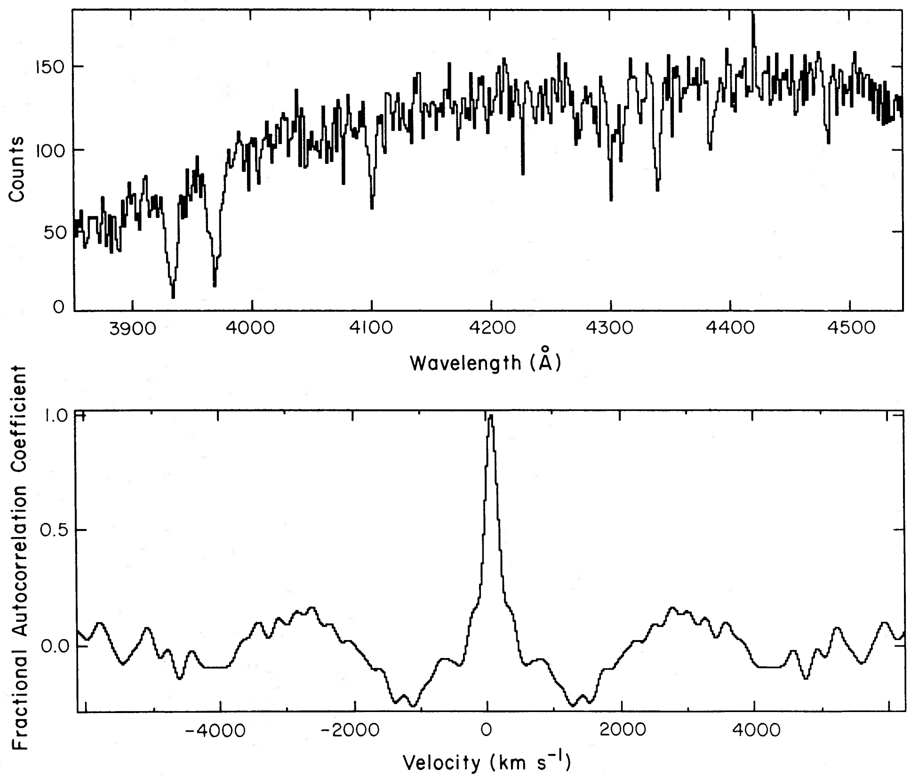

FIG. 1.—The spectrum (*upper panel*) and its autocorrelation of the reference star I-32 in NGC 188. The prominent absorption features at $\lambda 3933$ and $\lambda 3967$ are Ca II K and H.

Spectra of ER Cep and EQ Cep and their cross-correlations with star I-32 are shown in Figures 2 and 3. ER Cep is shown at two different orbital phases (Fig. 2), one near radial-velocity crossing and one near maximum separation. At velocity crossing the presence of only one cross-correlation peak suggests that the spectra of the two stars are superposed, while at the phase of maximum separation the appearance of two significant correlation peaks indicates that the velocities of the stellar components are resolved. For EQ Cep (Fig. 3), two correlation peaks are observed near the orbital phase of maximum velocity separation of the components.

The centers of Gaussians fit to the correlation peaks define the stellar radial velocities. At phases near radial-velocity crossing, one Gaussian was fitted; two Gaussians were fitted at other phases where two peaks (or blended peaks) are obvious. A cross-correlation peak is determined to be significant if its height has a confidence level above 97% (cf. Tony and Davis 1979). Although six different templates are cross-correlated against all the variables, only those peaks with significant correlation heights are fitted for velocities (see Table 1). Only the most significant portion of the cross-correlation peaks were fitted with Gaussians. The rms dispersions of the Gaussian fits to the correlation peaks are always much smaller than the precision later adopted for the radial velocities. The precision of the radial velocities (Table 1) is defined as the dispersion from the mean radial velocity measured for all those templates producing significant cross-correlation peaks with each variable-star spectrum.

At phases near radial-velocity crossing in ER Cep and ES Cep, the velocity of the center of the single cross-correlation peak is not significantly different from zero velocity relative to the cluster-template stars in NGC 188 and relative to the star in M67, once it has been corrected to the heliocentric velocity of NGC 188. For two spectra of ES Cep and one of ER Cep at phases near radial-velocity crossing, the four primary templates in NGC 188 yield an average velocity of -2 ± 15 km s^{-1}, where the precision is the standard deviation from the mean. The radial velocities of the center of mass in EP Cep and EQ Cep have not been measured but we assume they, too, are cluster members (Efremov *et al.* 1964). In the following we therefore assume that the velocity of the center of mass of EP Cep and EQ Cep binaries is the velocity of the reference stars in NGC 188.

Using the heliocentric velocity of the template star in M67, $V_{M67} = +33$ km s^{-1} (D. Latham, private communication), we determined the heliocentric velocity of all the observed template stars in NGC 188 to be -44 ± 6 km s^{-1}, where the error is one standard deviation of the mean of eight stars' radial velocities. This determination of the cluster radial velocity is in good agreement with the value of -49 km s^{-1} with a precision of ± 3 km s^{-1} measured by Greenstein and Keenan (1964) for all the giants presumed to be cluster members.

At phases when the radial velocities of the individual components are resolved, two Gaussians were fitted simultaneously to the cross-correlation peaks by the procedure described above. Two spectra at double-lined phases were obtained for EQ Cep. Only one spectrum at a double-lined phase was obtained for EP, ER, and ES Cep.

One spectrum of ER Cep (ZD 3104) at phase 0.96 was not used in the velocity analysis. At that phase ingress has begun. The component stars are nearly synchronous and have relatively large (~ 200 km s^{-1}) rotational velocities. During ingress, the spectrum of the eclipsed star can show a substantial redshift caused by the net rotation of the visible remnant of its

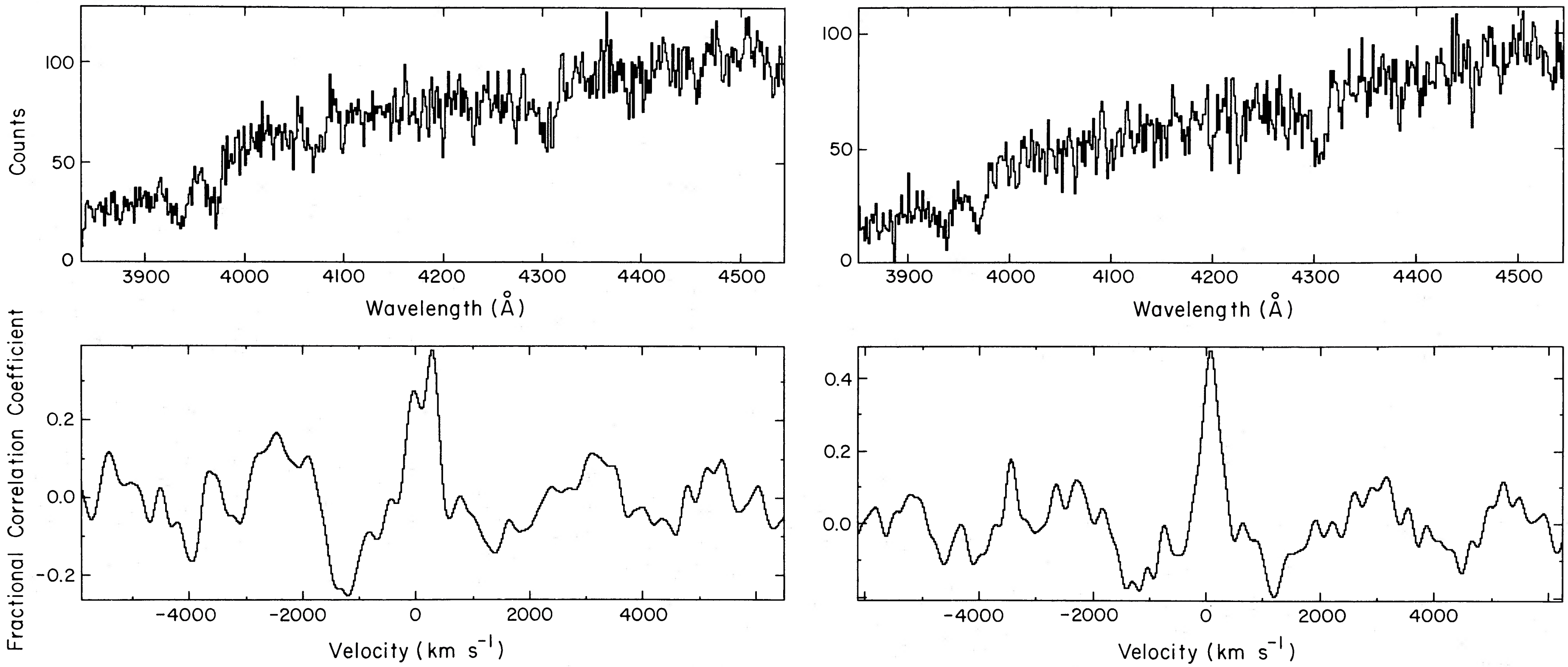

FIG. 2.—Spectra of ER Cep (*upper panels*) and cross-correlation coefficients between the spectra of ER Cep and that of the template star in NGC 188, I-32. The left panels show ER Cep at orbital phase $\phi = 0.79$, near maximum radial-velocity separation. Note two distinct peaks in the cross-correlation coefficients corresponding to the radial velocities of the component stars. The velocity separation of the stars is about 400 km s^{-1}. The right panels show the spectrum and cross-correlation coefficients for orbital phase $\phi = 0.62$, just past radial-velocity crossing. The individual stellar spectra are blended, as indicated by the single cross-correlation peak.

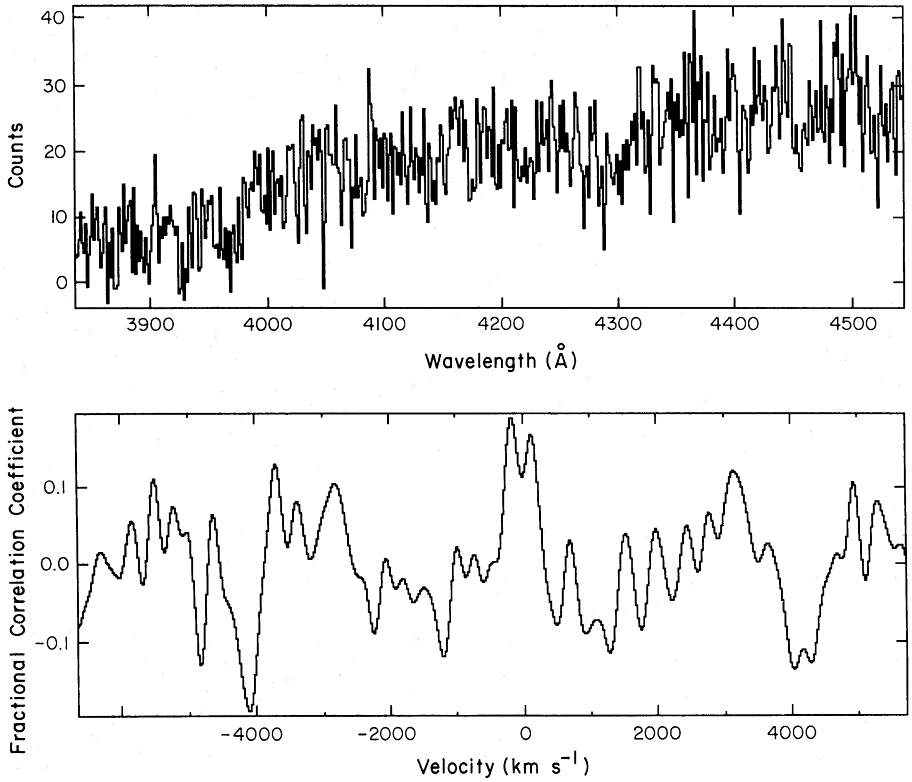

FIG. 3.—Spectrum of EQ Cep (*upper panel*) and cross-correlation coefficients (*lower panel*) calculated between the spectrum of EQ Cep and star I-32 at orbital phase $\phi = 0.30$, near maximum radial-velocity separation. The velocity separation of the two stars indicated by the two correlation peaks is about 300 km s^{-1}.

disk (cf. Rossiter 1924). The cross-correlations at this phase are actually resolved into two components, although the contributions to the velocities from the stars' orbital motions and the rotations are difficult to disentangle. The measured velocities are, however, documented for this spectrum in Table 1.

IV. RESULTS

a) Mass Ratios of the Binaries

The mass ratio q was measured for these stars from the ratio of the radial-velocity separations relative to the radial velocity of NGC 188, which is the assumed velocity of the center of mass of these binaries. The mass ratio is the ratio of the radial velocities of the hotter to cooler component stars and may be determined at any phase when both velocities are measurable from the relation:

$$q = M_h/M_c = |V_c - V_0|/|V_h - V_0| , \quad (1)$$

where V_h, M_h and V_c, M_c are the radial velocities and masses of the hotter and cooler components respectively, and V_0 is the center-of-mass radial velocity.

The determination of the mass ratio requires knowledge of the radial velocities of the components relative to the center of mass as well as the orbital orientation derived from the photometric phases. For double-lined spectroscopic binaries in the field, V_0 must be obtained from fairly complete radial-velocity curves. For these four binaries in NGC 188, the circumstance of cluster membership provides a unique advantage readily providing V_0.

The mass ratio q for the binaries in NGC 188 are listed in Table 3. The sense of the mass ratio has been determined from the photometric light curves (Kholopov and Sharov 1967*a*, *b*, *c*; Worden *et al.* 1978) combined with the radial velocities measured here. The uncertainty in the mass ratio (also listed in Table 2) is given by the standard deviation from the mean calculated only from those correlation peaks that were significant among the six possible template stars. In the case of EQ Cep the average value of q includes the results from spectra at two different phases. Along with the mass ratios in Table 3 are other observed parameters of these binaries, including their maximum V magnitudes, their observed and dereddened $(B-V)$ colors, the spectral types inferred from the dereddened colors, and their orbital periods.

The values of q found here are tentative because they are based only on a few spectra and, to a lesser extent, because a provisional value of the radial velocity of the mass center of each system was adopted. Specifically, we assumed V_0 to be the mean velocity of the four stars used as primary templates and listed in Table 2. This assumption is consistent with the velocities of ER and ES Cep observed near velocity crossing. The value of q found for EQ Cep appears to be best determined, since the mass ratios are derived from opposite quadratures of the orbit and yield essentially the same values of q. The mass ratios estimated for EP, ER, and ES Cep are based on only one spectrum each and are therefore uncertain. Although the mass ratio of ER Cep has been measured from only one spectrum, our value of $q = 0.65 \pm 0.11$ agrees well with that of the photometric value of $q = 0.59 \pm 0.11$ (from the W-case solution, see below), determined by Worden *et al.* (1978) from the analysis of their photoelectric B and V light curves. More spectra of all these stars are needed before definitive values of the mass ratios can be realized.

TABLE 3

CHARACTERISTICS OF THE W URSAE MAJORIS SYSTEMS IN NGC 188

Sonneberg Number	Star	m_v(max)[a]	$\langle B-V \rangle$[a]	$\langle B-V \rangle_0$[b]	Sp.[c]	Period[d] (days)	m_h/m_c[e]	Type[f]
S8278	EQ Cep	+16.25	+0.90	+0.83	K0(V)	0.3069	0.41 ± 0.12	W
S8279	ER Cep	+15.65	+0.83	+0.76	G9(V)	0.2857	0.65 ± 0.11	W
S8280	ES Cep	+15.52	+0.88	+0.81	K0(V)	0.3424	0.11: ± 0.05	W
S8474	EP Cep[g]	+16.6:	+0.9:	+0.83:	K0(V):	0.2897	0.30: ± 0.30	W

[a] From Eggen and Sandage 1969.
[b] $E_{B-V} = 0.07$ adopted from Twarog 1978.
[c] Spectral types inferred from the dereddened colors using the relation between spectral type and $(B - V)$ given by Novotny 1973.
[d] From Kholopov and Sharov 1967*a*, *b*, *c*.
[e] Ratio of masses of hotter and cooler components. Errors are standard deviations determined from velocities derived from cross-correlations at two different orbital phases of EQ Cep, one phase of EP Cep, ER Cep, and ES Cep, and with a number of different template stars in each case as indicated in Table 1.
[f] A contact binary is classified as "W-type" if the least massive star is eclipsed at primary light minimum.
[g] A colon denotes uncertain parameters for the faintest star, EP Cep.

The mass ratios for the four W UMa–type binaries in NGC 188 are smaller than unity and correspond to the "W-type" contact-binary systems (Binnendijk 1965). In a W-type system, the less massive, secondary component is the hotter of the two and its occultation produces the deeper light-curve minimum. The distinction for W-type contact binaries, in contrast to the A-type systems, is that W-type systems are later in spectral type and less massive than those of the A-type (Rucinski 1974; Wilson 1978).

These W UMa–type binaries in NGC 188 have properties similar to the W-type systems in the field (Rucinski 1974; Mochnacki 1981). To illustrate this we have plotted EP, EQ, ER, and ES Cep in the period-color diagram of W UMa–type systems (Fig. 4). The field W UMa–type binaries listed by Mochnacki (1981) that have reliable A- or W-type classifications are also plotted in the figure. The mean period-color relation found by Eggen (1967) is also shown. The four W UMa–type binaries of NGC 188 are very close to Eggen's period-color relation, and all four cluster variables are located in the portion of the diagram which is populated by W-type systems.

The positions of EP, EQ, ER, and ES Cep in the color-magnitude diagram of NGC 188 are shown in Figure 5. The

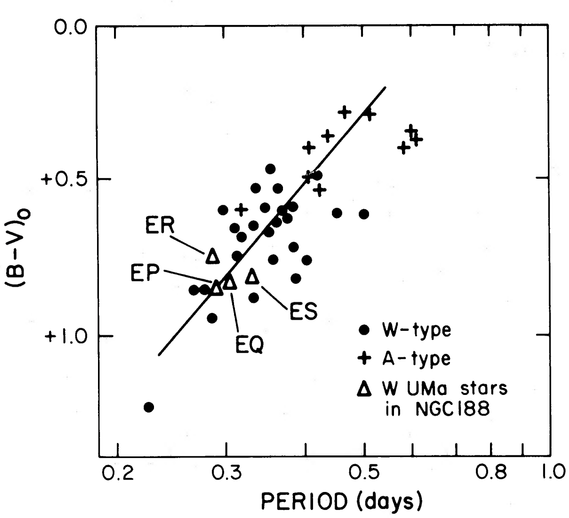

FIG. 4

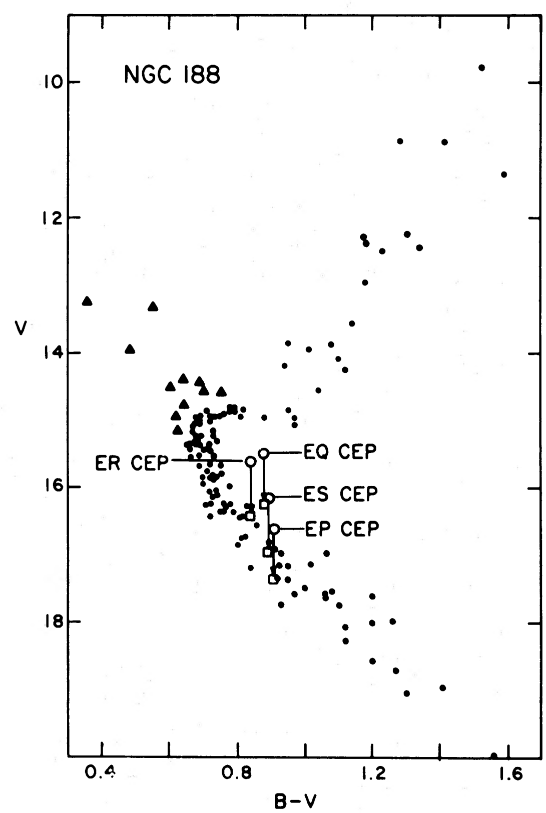

FIG. 5

FIG. 4.—The dereddened color $(B-V)_0$ versus the orbital period for classical W UMa–type binaries, from Mochnacki (1981). The four W UMa–type systems found in NGC 188 are identified and lie in the region of W-type systems in the field. The line represents the period-color relation for W UMa–type stars from Eggen (1967).

FIG. 5.—The observed color-magnitude diagram of NGC 188 adopted from Eggen and Sandage (1969). The observed V magnitudes and $(B-V)$ colors are shown for the combined light of each of the four W UMa–type binaries (*open circles*). The colors and magnitudes for the individual component stars are also shown (*open squares*). These values assume the components contribute equally to its system's light. Blue stragglers are shown as triangles.

color-magnitude diagram of the cluster was adopted from Eggen and Sandage (1969) and does not include corrections for interstellar absorption and reddening. The V magnitudes and $(B-V)$ colors of the four binaries at maximum light are plotted (see Table 3). These values are the combined light and colors of the components of each binary. Also plotted in the figure are the inferred V magnitudes for a single component of each system that were computed under the assumption that the component stars contribute equally to their total system brightness. This approximation is satisfactory for W UMa–type binaries whose component masses are comparable, as in the case of ER Cep with $q \approx 0.6$. We have not corrected the individual magnitudes and colors of the other systems with the measured values of q because there are no precise photoelectric B and V light curves available, and in addition the values of q for two of them (EP and ES Cep) are not well determined. As seen in Figure 5, the component stars of these systems appear to lie on or very close to the main-sequence branch of the cluster.

b) *Absolute parameters of ER Cephei*

Combined with the photometric elements derived by Worden *et al.* (1978) from their photoelectric light curves, our spectroscopic mass ratio tentatively yields the absolute physical quantities of ER Cep (Table 3). In order to determine the physical parameters of the individual stars, we have assumed that the orbital phases calculated from the ephemeris of Worden *et al.* (1978) have remained accurate for the epoch of our observations and that the mass ratio is reasonably accurate. The radial velocity semi-amplitudes of the hot and cool components were computed from

$$K_{h,c} = |(V_{h,c} - V_0)/\sin\theta| , \quad (2)$$

where θ is the orbital phase (in degrees) at which the observations were made. For ER Cep, $\theta = 0.79P = 284°$. The other quantities given in the table were computed using the conventional formulae given in Binnendijk (1960). Comparison of the physical properties of the components of ER Cep given in Table 3 with those of other W UMa–type systems with similar orbital periods (cf. Mochnacki 1981), indicates that it is a typical W-type system. The same conclusion was reached by Whelan *et al.* (1979) in their spectroscopic and photometric study of AH Cnc—a W-type W UMa binary in the open cluster M67. Although the mass ratio of EQ Cep is reasonably well determined, no photoelectric light curve exists from which to extract the physical parameters of the component stars. We conclude that except for their memberships in old star clusters, nothing appears to distinguish these binaries from their relatives in the field.

TABLE 4

CHARACTERISTICS OF ER CEPHEI

Parameter	Value
Photometric Elements[a]	
Orbital period	0^{d}2857355
Eccentricity (assumed)	0.0
From the W-type solution:	
Inclination (i)	78°
Mass ratio (q)	0.59 ± 0.11
Fill-out factor	1.02
Mean $T_{eff}(T_h \approx T_c)$	5330 K
Fractional radius, cooler star	0.42
Fractional radius, hotter star	0.33
Provisional Spectroscopic Elements[b]	
System type	W-type
$K_1(= K_{cool})$	~149 km s^{-1}
$K_2(= K_{hot})$	~226 km s^{-1}
M_2/M_1	0.66
$a_1 \sin i$	5.9 × 10^5 km
$a_2 \sin i$	8.9 × 10^5 km
$a \sin i$	1.48 × 10^6 km
$M_1 \sin^3 i$	0.91 $M_\odot$
$M_2 \sin^3 i$	0.60 $M_\odot$
Absolute Quantities	
Semimajor axis of orbit (A)	2.17 $R_\odot$
Total system mass	1.61 $M_\odot$
Total luminosity[c]	~1.1 $L_\odot$
Age (= cluster age)	5 × 10^9 yr
Hotter component:	
Mass	0.64 $M_\odot$
Radius	0.72 $R_\odot$
Cooler component:	
Mass	0.97 $M_\odot$
Radius	0.91 $R_\odot$

[a] From Worden *et al.* 1978.
[b] From MMT spectra, 1983 July.
[c] Adopting a distance modulus of the cluster of $(m - M)_V = +10.85$ mag (Twarog 1978).

V. DISCUSSION

a) *The Ages of the Field W Ursae Majoris Binaries*

One long-standing question concerning the W UMa binaries has been their evolutionary status. To determine the ages of the W UMa stars in the field is difficult.

The mass ratios of EP, EQ, ER, and ES Cep and the absolute quantities of ER Cep suggest that these four contact-binary systems are similar physically to those in the field (cf. Fig. 4). If coeval with the cluster NGC 188, however, these cluster binaries have an age of between 5 and 10 × 10^9 yr, the nuclear age of NGC 188 (Sandage 1962; Janes and Demarque 1983; VandenBerg 1983). Alternatively, van't Veer (1982) has suggested that these binaries, although cluster members, were only recently formed. There is no corroborative evidence, however, of recent star formation in this cluster.

The kinematic properties of field W UMa–type binaries indicate that they are chiefly members of the intermediate disk population of stars and are thus relatively old (Artiukhina 1964; Eggen 1967). Furthermore, their spatial distribution shows only a moderate concentration toward the galactic plane (Popov 1964; Kraft 1965) and is consistent with their membership in the disk population.

An upper limit on the ages of W UMa–type stars can be estimated from their distribution and frequency of occurrence among the older Population II stars of the Galaxy. Several W UMa binaries have been discovered in surveys for RR Lyrae–type variables among red variables in the galactic halo (Kinman, Wirtanen, and Janes 1966; Kinman, Mahaffey, and Wirtanen 1982). The RR Lyrae variables, occurring as they do in the halo and in globular clusters, are good tracers of Population II objects. The fields surveyed by Kinman *et al.* indicate that the W UMa stars populate *not* the halo, but rather the disk. The W UMA–type variables occur relatively infrequently (2 W UMa–type, 44 RR Lyrae–type) in fields toward the north galactic pole (Kinman, Wirtanen, and Janes 1966). The W UMa stars are more common (10 W UMa–type, 25 RR Lyrae–

type) in fields toward the galactic anticenter (Kinman, Mahaffey, and Wirtamen 1982). The anticenter fields include a significant contribution from the disk population. The lack of W UMa variables in any globular clusters (Kukarkin 1973; Trimble 1980; Webbink 1980) further substantiates that the W UMa stars are members of the intermediate-age disk population and not extremely old. An upper limit on their ages is likely $\sim 10^{10}$ yr.

b) Ages of W Ursae Majoris Binaries Inferred from Cluster Membership

Currently several W UMa binaries are known to be open-cluster members: TX Cnc in Praesepe (age: $t \approx 5 \times 10^8$ yr), AH Cnc in M67 ($t \approx 3 \times 10^9$ yr), AH Vir in Wolf 630 ($t \approx 3 \times 10^9$ yr), and our four variables in NGC 188 ($t \approx 5$–10×10^9 yr). The system RZ Com is a suspected member of Coma ($t \approx 3 \times 10^9$ yr). From their kinematic and spatial distribution discussed above, the field W UMa binaries probably have ages between 5×10^8 and 1×10^{10} yr as well.

The presence of low-mass W UMa–type binaries in young clusters is controversial and not established (van't Veer 1975, 1980; Rucinski 1980). Membership of the massive, hot contact binaries has been proposed for a few young galactic clusters, for example, BH Cen (Leung *et al.* 1984) and LW Cen (Thackeray 1964) in IC 2994, or V701 Sco in NGC 6383 (Wilson and Leung 1977). These hot contact binaries consists of pairs of B stars and are frequently associated with the classical W UMa stars because of their similarly shaped light curves. There are, however, large differences between these two kinds of binary star system. The hot contact systems are more massive, with system masses greater than about 5 $M_\odot$, and more luminous, with total luminosities in excess of about 100 $L_\odot$, than the low-mass, classical W UMa–type binaries which consists of a pair of solar-like stars. Currently, no low-mass W UMa–type binary has been definitely identified in a star cluster younger than Praesepe or Coma ($t \approx 5 \times 10^8$ yr), despite fairly thorough searches of young, open clusters such as the Pleiades ($t \approx 7 \times 10^7$ yr), h and χ Persei ($t \approx 3 \times 10^7$ yr), and the Hyades ($t \approx 5 \times 10^8$ yr).

We infer that W UMa–type systems are relatively rare among young populations of stars. In addition, there is no convincing evidence for the presence of W UMa–type stars among the very old, Population II stars of globular clusters. The W UMa–type stars, therefore, represent a temporary evolutionary state whose problematic origin and future lack quantitative understanding.

c) The Frequency of W Ursae Majoris–Type Binaries in NGC 188

The cluster NGC 188 is the only one so far studied that possesses more that one W UMa–type system. The presence of at least four W UMa–type binaries in NGC 188 indicates that the local space density of these binaries is at least $\sim$20–50 times their mean space density in the solar neighborhood.

The relatively large light amplitudes observed for these stars range from 0.6 to 0.9 mag and indicate that these systems have orbital inclinations higher than 60° relative to the plane of the sky. Indeed, the analysis of the photoelectric light curve of ER Cep by Worden *et al.* (1978) yields a high orbital inclination i of about 78°. If we assume that the axes of the orbits of these binaries are randomly oriented in space, then *at least* eight more W UMa–type systems are expected to reside within the cluster. Half of these with inclinations of $60° \lesssim i \lesssim 30°$ should be detectable because their light variations would range from 0.2 mag up to 0.5 mag. The expected systems with orbital inclinations $i \lesssim 30°$ will be difficult to detect using conventional photometric or spectroscopic techniques. It is important to search the cluster for these additional members in order to test whether the orbital axes of the stars are randomly oriented in the cluster. The existence or nonexistence of these additional close binary systems in NGC 188 and other old open clusters could have important ramifications in our understanding of the formation and dynamics of star clusters, as well as binary star evolution.

d) Evolution of the W Ursae Majoris Stars

The spatial incidence of W UMa–type binaries in NGC 188 appears to be much higher than in any other open cluster studied or in the field. The discriminating factor in the case of NGC 188 is its great age. The scarcity of significant numbers of W UMa–type binaries among the younger, and usually better searched, clusters, and among Population I stars indicates that this type of close binary generally does not emerge on the zero-age main sequence in the contact configuration. The preponderance of W UMa–type binaries only near the age of NGC 188 suggests that the contact state is a consequence of rather lengthy main-sequence evolution. Models that produce the contact phase by angular momentum loss from the binary system predict that the contact configuration is relatively short-lived, with a lifetime shorter than about 5–10 $\times 10^8$ yr (Vilhu 1982; Patterson 1984). Thus, the great age and relatively short lifetimes of the W UMa–type binaries imply that they have evolved into the contact state from detached or semidetached progenitors. Angular momentum loss may be provided by magnetic torques in a stellar wind, the same mechanism that slows the rotation of single cool dwarf stars during their main-sequence lifetimes (Huang 1966; Mochnacki 1981; Vilhu 1982; Patterson 1984). In fact, the decrease in rotation proportional to the inverse square root of the main-sequence age of a single, cool dwarf star (Skumanich 1972; Soderblom 1983) reasonably accounts for the properties of the contact binaries—for example, their space densities, orbital periods, and ages in the intermediate-age and old open clusters (cf. Vilhu 1982). The stellar components of the contact binaries and their more widely separated progenitors are tidally forced into rotation synchronous with their orbits. Spin angular momentum loss, therefore, is tidally coupled to orbital angular momentum loss in these systems; the loss of orbital angular momentum produces the decrease of orbital separation with time.

The apparent scarcity, or really the nonexistence, of W UMa–type binaries in extremely old populations of stars can be explained by the ultimate destruction of these systems by the coalescence mechanism suggested by Webbink (1976). According to Webbink's evolutionary model, the final coalescence of a contact binary occurs after the completion of hydrogen burning in the core of the more massive binary member. The apparent lack of W UMa–type systems in extremely old stellar populations, therefore, can be explained by the fact that they have coalesced into single stars! Recently Bopp and Rucinski (1981) have suggested that the peculiar, rapidly rotating G giant star FK Com has evolved from a W UMa–type system according to the Webbink evolutionary scheme. It is important to note that FK Com has the kinematic and spatial properties of an *old* disk population star (Dorren, Guinan and McCook 1984) as well as the total angular momentum of a typical W UMa–type system, in accord with its proposed evolutionary status. Further evidence for FK Comae stars evolving from the W UMa–type binaries is provided by the discovery of a rapidly rotating, apparently single G8 IIIb star in NGC 188 itself, star I-1 (Harris and McClure 1985). Its projected rotational velocity $v \sin i$ is measured to be about 24 km s^{-1}. While the rotation of I-1 is not as inordinate as the approximately 100 km s^{-1} typical of other FK Comae–stars, I-1 displays excessive angular momentum for its spectral type. As Harris and McClure (1985) suggest, this giant is likely an aging FK Comae–type star whose angular velocity has quickly slowed (cf. Webbink 1976).

VI. SUMMARY

We have confirmed with spectroscopic studies that the four short-period variables EP, EQ, ER, and ES Cep in NGC 188 are indeed W-type classical W UMa–type stars. The stars ER Cep and ES Cep at phases of radial-velocity crossing show systemic velocities consistent with cluster membership. These are the only two variables tested so far for membership by a radial velocity criterion. All four variables have a location in space and in the cluster color-magnitude diagram consistent with cluster membership.

The mere presence of these contact binaries in a galactic cluster as old as NGC 188, whose age is $\sim$5–10 $\times$ 10^9 yr, determines their age. Further, no W UMa binaries have so far been found in clusters younger than the Praesepe or Coma or older than NGC 188. The space velocities of the W UMa systems in the field indicate that they too are relatively old and disk-population members. With a relatively short lifetime in the contact configuration, most likely less than $\sim$5–10 $\times$ 10^7 yr, the great age of the contact binaries means they have evolved from detached or semidetached binary systems. The progenitor systems may lose angular momentum by means of magnetic torques in stellar winds, much the same as single stars do. Tidal forces convert the spin angular momentum loss to orbital angular momentum loss. The W UMa–type binaries may coalesce into apparently single FK Comae–type stars.

We would like to thank the staff of the MMT and F. L. Whipple Observatories for their hospitality and assistance in this observing project. We appreciate the generous support of the Langley-Abbot Fund of the Smithsonian. We thank Dr. Graeme Smith for the use of his spectra of M3 AV and M67 T829 and template stars in NGC 188. We are indebted to Drs. K.-C. Leung, S. Rucinski, Allen Sandage, and Graeme Smith for useful discussions.

REFERENCES

Artuikhina, N. M. 1964, *Perem Zvezdy*, **15**, 127.
Baliunas, S. L., and Guinan, E. F. 1983, *Bull. AAS*, **15**, 924.
———. 1984, in *Cool Stars, Stellar Systems and the Sun*, ed. S. L. Baliunas and L. Hartmann (New York: Springer), p. 223.
Binnendijk, L. 1960, *Properties of Double Stars* (Philadelphia: University of Pennsylvania Press), p. 148.
———. 1965, in *3d IAU Colloquium on Variable Stars, The Position of Variable Stars in the Hertzsprung-Russell Diagram*, ed. W. Strohmeier (Kleine Veröff. Bamberg, Vol. **40**, No. 40), p. 36.
———. 1970, in *Vistas Astr.*, **12**, 211.
Bopp, B. W., and Rucinski, S. M. 1981, in *IAU Symp. 93, Fundamental Problems in the theory of Stellar Evolution*, ed. D. Sugimoto, D. N. Schramm, and D. Q. Lamb (Boston: Reidel), p. 177.
Budding, E. 1982, in *Binary and Multiple Stars as Tracers of Stellar Evolution*, ed. Z. Kopal and J. Rahe (Boston: Reidel), p. 351.
Cruddace, R. G., and Dupree, A. K. 1984, *Ap. J.*, **277**, 263.
Dorren, J. D., Guinan, E. F., and McCook, G. P. 1984, *Bull. AAS*, **16**, 474.
Eaton, J. A. 1983, *Ap. J.*, **268**, 800.
Efremov, Y. N., Kohlopov, P. N., Kukarkin, B. V., and Sharov, A. S. 1964, *Inf. Bull. Var. Stars*, No. 75.
Eggen, O. J. 1967, *Mem. R.A.S.*, **70**, 111.
Eggen, O. J., and Sandage, A. 1969, *Ap. J.*, **158**, 669.
Greenstein, J. L., and Keenan, P. C. 1964, *Ap. J.*, **140**, 673.
Harris, H. C., and McClure, R. D. 1985, *Pub. A.S.P.*, in press.
Hazelhurst, J. 1970, *M.N.R.A.S.*, **149**, 129.
Hoffmeister, C. 1964, *Inf. Bull. Var. Stars*, No. 67.
Hrivnak, B. J., Milone, E. F., Hill, G., and Fisher, W. A. 1984, *Ap. J.*, **285**, 683.
Huang, S.-S. 1966, *Ann. d'Ap.*, **29**, 331.
Janes, K., and Demarque, P. 1983, *Ap. J.*, **264**, 206.
Janes, K. A., and Smith, G. H. 1984, *Ap. J.*, **89**, 487.
Kholopov, R. N., and Sharov, A. S. 1967*a*, *Astr. Circ. USSR*, No. 426.
———. 1967*b*, *Astr. Circ. USSR*, No. 434.
———. 1967*c*, *Astr. Circ. USSR*, No. 452.
Kinman, T. D., Wirtanen, C. A., and Janes, K. A. 1966, *Ap. J. Suppl.*, **13**, 379.
Kinman, T. D., Mahaffey, C. T., and Wirtanen, C. A. 1982, *Ap. J.*, **87**, 314.
Kopal, Z. 1955, *Ann. d'Ap.*, **29**, 331.
Kraft, R. P. 1965, *Ap. J.*, **135**, 408.
Kukarkin, B. V. 1973, in *Variable Stars in Globular Clusters and Related Systems*, ed. J. D. Fernie (Boston: Reidel), p. 8.
Latham, D. W. 1982, in *Instrumentation for Astronomy with Large Optical Telescopes*, ed. C. M. Humphries (Boston: Reidel), p. 259.
Leung, K. C., Sistero, R. F., Zhai, D.-S., Grieco, A., and Candellero, B. 1984, *A.J.*, **89**, 872.
Lucy, L. B. 1968, *Ap. J.*, **151**, 1123.
———. 1976, *Ap. J.*, **205**, 208.
———. 1977, *A.J.*, **82**, 1023.
McLean, B. J. 1981, *M.N.R.A.S.*, **195**, 931.
McLean, B. J. 1983, *M.N.R.A.S.*, **204**, 817.
McLean, B. J., and Hilditch, R. W. 1983, *M.N.R.A.S.*, **203**, 1.
Mochnacki, S. W. 1981, *Ap. J.*, **245**, 650.
Murray, C. A., and Clements, E. D. 1968, *Royal Obs. Bull.*, No. 139.
Norris, J., and Smith, G. H. 1984, *Ap. J.*, **287**, 255.
Novotny, E. 1973, *Introduction to Stellar Atmospheres and Interiors* (New York: Oxford University Press), p. 10.
Patterson, J. 1984, *Ap. J. Suppl.*, **54**, 443.
Popov, M. V. 1964, *Perem Zvezdy*, **15**, 115.
Rossiter, R. A. 1924, *Ap. J.*, **60**, 15.
Rucinski, S. M. 1974, *Acta Astr.*, **24**, 119.
———. 1980, *Acta Astr.*, **30**, 373.
Rucinski, S. M., and Vilhu, O. 1983, *M.N.R.A.S.*, **202**, 1221.
Sandage, A. 1962, *Ap. J.*, **135**, 333.
Sandage, A., and Katem, B. 1982, *Ap. J.*, **87**, 637.
Shu, F. H., Lubow, S. H., and Anderson, L. 1976, *Ap. J.*, **209**, 536.
———. 1979, *Ap. J.*, **229**, 223.
Skumanich, A. 1972, *Ap. J.*, **171**, 565.
Soderblom, D. 1983, *Ap. J. Suppl.*, **53**, 1.
Thackeray, A. D. 1964, in *IAU Symposium 20, The Galaxy and the Magellanic Clouds*, ed. F. J. Kerr and A. W. Rogers (Canberra: Australian Acad. Sci.), p. 18.
Tonry, J., and Davis, M. 1979, *A.J.*, **84**, 1511.
Trimble, V. L. 1980, in *IAU Symposium 85, Star Clusters*, ed. J. E. Hesser (Boston: Reidel), p. 259.
Twarog, B. A. 1978, *Ap. J.*, **220**, 890.
VandenBerg, D. A. 1983, *Ap. J. Suppl.*, **51**, 29.
van't Veer, F. 1975, *Astr. Ap.*, **44**, 437.
———. 1979, *Astr. Ap.*, **80**, 287.
———. 1980, *Acta Astr.*, **30**, 381.
———. 1982, in *IAU Colloquium 69, Binary and Multiple Stars as Tracers of Stellar Evolution*, ed. Z. Kopal and J. Rahe (Boston: Reidel), p. 279.
Vilhu, O. 1982, *Astr. Ap.*, **109**, 17.
Vilhu, O., and Rahunen, T. 1980, in *IAU Symposium 88, Close Binary Stars: Observations and Interpretations*, ed. M. J. Plavec, D. M. Popper, and R. K. Uhlrich (Boston: Reidel), p. 141.
Webbink, R. F. 1976, *Ap. J.*, **209**, 829.
———. 1980, in *IAU Symposium 88, Close Binary Stars: Observations and Interpretations*, ed. M. J. Plavec, D. M. Popper, and R. K. Uhlrich (Boston: Reidel), p. 561.
Whelan, J. A. J., Worden, S. P., Rucinski, S. M., and Romanishin, W. 1979, *M.N.R.A.S.*, **186**, 729.
Wilson, R. E. 1978, *Ap. J.*, **224**, 885.
Wilson, R. E., and Leung, K.-C. 1977, *Ap. J.*, **211**, 853.
Worden, S. P., Coleman, G. D., Rucinski, S. M., and Whelan, J. A. J. 1978, *M.N.R.A.S.*, **184**, 33.

S. L. Baliunas: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
E. F. Guinan: Astronomy Department, Villanova University, Villanova, PA 19085