The Origins, Evolutions, and Destinies of Binary Stars in Clusters
ASP Conference Series, Vol. 90, 1996
E.F. Milone and J.-C. Mermilliod (eds.)

The Distance Modulus of NGC 188 inferred from Eclipsing Binary Light Curve Solutions

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NGC 188 is an old galactic cluster with an age of 10 Gyr, a color excess E_{B-V} of $0\overset{\mathrm{m}}{.}08$, and a distance modulus $V - M_V = 11\overset{\mathrm{m}}{.}1$, according to VandenBerg (1985). Recently, Twarog and Anthony-Twarog (1989) argued that the cluster is considerably younger with an age of 6.5 ± 0.5 Gyr, a color excess $E_{B-V} = 0\overset{\mathrm{m}}{.}12$ and a distance modulus $V - M_V = 11\overset{\mathrm{m}}{.}5$. We attempt to resolve these differing age and distance estimates by having a closer look at NGC 188's eclipsing binaries. Using the method of Wilson and Devinney (1971) and Wilson (1979), we solve the V-light curves of EQ, ER, ES, and V369 Cep obtained by Kaluzny (1990), and the B-light curve of EP Cep observed by Kaluzny and Shara (1987). Light curve solutions yield relative radii and also mass ratios since the systems are either semi-detached, close to contact, or over-contact. Since contact or near-contact W UMa-type systems have relatively un-evolved primary components, we can estimate their masses using a suitable color-mass main sequence relationship. At least, in principle, the distance to the system and hence to the cluster can then be determined.

Following Van Hamme and Wilson (1985), we write the distance modulus of the primary component of a binary system as

$$V - M_V = -39.19 + V + BC + 10\log T + 5\log r + \frac{5}{3}\log M_1 + \frac{10}{3}\log P + \frac{5}{3}\log(1+q). \tag{1}$$

BC is the star's bolometric correction, T its effective temperature, r its relative radius, M_1 the mass of the primary in $M_\odot$, P the orbital period in days, and $q = M_2/M_1$ the mass ratio. The constant term is based on $M_{\mathrm{bol}\odot} = 4\overset{\mathrm{m}}{.}69$ and $T_\odot = 5780\,\mathrm{K}$. The standard deviation of the distance modulus is obtained using the error propagation formula

$$\sigma^2_{V-M_V} = \sigma^2_V + \left(\frac{\partial BC}{\partial(B-V)} + 10\frac{\partial \log T}{\partial(B-V)}\right)^2 \sigma^2_{B-V} +$$

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$$+\left(\frac{5}{3\ln 10}\right)^2\left(\frac{9}{r^2}\sigma_r^2+\frac{1}{M_1^2}\sigma_{M_1}^2+\frac{4}{P^2}\sigma_P^2+\frac{1}{(1+q)^2}\sigma_q^2+\frac{6}{r(1+q)}\rho_{rq}\sigma_r\sigma_q\right). \quad (2)$$

For r we use the equal-volume radius of the primary component. The correlation coefficient between r and q, ρ_{rq}, is obtained via the correlation between q and the surface potential Ω. The apparent V-magnitude and standard error (corrected for interstellar extinction) are the mean and standard deviation of the magnitudes observed around phase $0^{\mathrm{P}}.75$. This magnitude is for the combined system of two stars. The magnitude of the primary component can be calculated by taking into account the fraction of the total light at phase $0^{\mathrm{P}}.75$ contributed by each individual star according to the light curve solution. T, BC, and numerical estimates for the partial derivatives in Eqn. (2) were computed using a cubic spline interpolation in the appropriate calibrations listed in Lang (1992). Using $M_{\mathrm{bol}\odot} = 4^{\mathrm{m}}.75$ and the BC-color scale of Allen (1976) decreases the constant in Eqn. (1) by $0^{\mathrm{m}}.06$ and increases BC by a similar amount, yielding essentially the same distance modulus. We assume a typical standard deviation of $0^{\mathrm{m}}.013$ for the $B-V$ color index in accordance with Johnson and Morgan (1953). Masses were computed from $B-V$ colors using results of a weighted linear least squares fit of mass vs. $B-V$ for main sequence stars with $B-V > 0.50$, compiled by Andersen (1991) and Popper (1993). A 15% standard deviation for M_1 is used in Eqn. (2) to reflect the width of the main sequence color-mass relationship. For the over-contact binaries, $B-V$ colors were corrected for luminosity transfer between components using the method of Mochnacki (1981) and modified to account for a change not only in temperature but also in radius.

System	$E_{B-V} = 0.08$	$E_{B-V} = 0.12$
EP Cep	10.78 ± 0.15	10.83 ± 0.15
EQ Cep	11.26 ± 0.12	11.28 ± 0.13
ER Cep	10.70 ± 0.13	10.78 ± 0.12
ES Cep	10.76 ± 0.12	10.80 ± 0.11
V369 Cep	11.44 ± 0.12	11.56 ± 0.12
Mean	11.014 ± 0.057	11.049 ± 0.055

Table 1. NGC 188 distance moduli

Our results are not greatly affected by the assumed amount of reddening and appear to be, for 3 out of 5 systems, in favor of favor the VandenBerg (op. cit.) distance modulus for NGC 188. However, our light curve solutions are preliminary in nature. For EP Cep, we only have a B-light curve with modest phase coverage. The other systems have well-covered light curves in V but only sparsely covered B curves. The light curves show asymmetries which were modeled using spots. New multi-color light curves are needed and solutions of existing curves need to be fine-tuned. Radial velocities would help to reduce uncertainties in the absolute masses and radii.

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