JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: S89 ∼ S91, 1996

ECLIPSING BINARY STARS IN THE MAGELLANIC CLOUDS

WILLIAM TOBIN
Mt John University Observatory and Department of Physics & Astronomy
University of Canterbury, Private Bag 4800, Christchurch, New Zealand

ABSTRACT

Within the next few years eclipsing binaries should yield primary distance measurements for the Magellanic Clouds as well as provide tests of theoretical low-metallicity stellar models.

Key Words : eclipsing binary stars, Magellanic Clouds, stellar evolution, distance indicators

I. INTRODUCTION

Eclipsing binaries in the Magellanic Clouds are currently of interest:

1) For tests of models of stellar structure and evolution at low metallicity (Milky Way, $z{\sim}0.020$; LMC, $z{\sim}0.008$; SMC, $z{\sim}0.004$), and

2) As primary distance indicators.

Masses and radii for comparison with theoretical models are derived from radial-velocity and differential light curves. Luminosities and hence distances come from coupling the stellar surface areas with surface fluxes determined from absolute photometry and spectrophotometry. As explained below, only excellent data will yield worthwhile accuracy, but with modern instruments and detectors this should with care be achievable for brighter systems in the Clouds.

This work is timely because of the recent availability of theoretical calculations at low metallicity: evolutionary models (Schaerer *et al.* 1993, Charbonnel *et al.* 1993, Claret & Giménez [including apsidal constants—see below] 1992, 1995) and stellar atmospheres (Kurucz 1993). The requisite analysis codes (e.g. EBOP, LIGHT2, Wilson) have been available for some time.

II. DISCOVERY

The discovery of eclipsing binaries in the Magellanic Clouds resulted from observations at Harvard's high-altitude Boyden Station in Arequipa, Peru, and particularly from plates taken with the 24-inch, f/5.5 Bruce Astrograph. An early catalogue of variable stars in the Clouds was produced by Leavitt (1908). Eclipsing binaries were initially taken to be foreground objects, but as their number increased it became clear they were Cloud members (Shapley & McKibben [Nail] 1942, 1952). Final 'HV' lists incorporating further plate material were published by Gaposchkin (1965; SMC, 33 systems: see Payne-Gaposchkin & Gaposchkin 1966 for coordinates) and Payne-Gaposchkin (1971, LMC, 78 systems). Photographic mean light curves were published by Gaposckhin (1965, SMC; 1970, LMC). He listed eclipse timings spanning ∼1896–1953 for 76 LMC systems (along with light-curve tabulations for both Clouds) in 1977. Smaller-scale photographic surveys have uncovered a handful of other eclipsing binaries (e.g. Dartayet & Dessy 1952, SMC; Butler 1978, LMC).

Further discoveries are being made as by-products of the current spate of microlensing surveys. These surveys are using arrays of CCDs to search for possible dark matter in the halo of our Galaxy. The effect sought is the brightening of a star in the Magellanic Clouds due to gravitational microlensing when a massive compact object cuts across the line of sight. The surveys are monitoring 10^5–10^6 stars in the Clouds and discovering myriad variable stars. A catalogue of 79 probable eclipsing binaries discovered in a $1^\circ \times 0.4^\circ$ field in the LMC bar has been published by the French EROS project (Grison *et al.* 1995), while the Australian-American MACHO team reports the detection of 1200 systems in a somewhat larger region also centered on the bar (Cook *et al.* 1995). However reduction and/or analysis (not to mention publication) are still needed for the vast majority of the observations collected by these surveys, especially for less-crowded fields where follow-up observations will be easiest.

The magnitudes and such colours as are available for the known systems indicate predominantly main sequence or near-main sequence O-, B- or A-type stars. Contact, semi-detached and detached systems are present.

The large number of eclipsing binaries being found by the microlensing surveys obviously raises hopes for statistical studies. However, evaluation of magnitude-dependent selection effects may be tricky, especially with respect to crowding and the algorithms for period-finding and recognition, particularly if full procedural details are not published. As a warning, it has transpired that owing to a coding error, systems with periods close to integer multiples and submultiples of 1 day are absent from the EROS catalogue (Beaulieu, private comm.).

III. OBSERVATIONAL REQUIREMENTS

The systems most amenable to accurate analysis and interpretation are edge-on, double-lined systems with well-separated (i.e. near-spherical) components that have not undergone any mass transfer. Such systems can be selected from CCD microlensing surveys with confidence, but photographic light curves are only indicative of a system's nature.

As has been emphasized by Andersen (1991), masses and radii accurate to 1-2% are a prerequisite for meaningful tests of the precise effects of main-sequence evolution, opacity, convection and metallicity.

For this, better than 1% differential photometry is needed. The fields in the Clouds are generally too crowded for satisfactory single-channel photometry with photomultipliers (e.g. Davidge 1987, 1988). CCDs and crowded-field reduction software are required. Using the 1.54-m Danish telescope at La Silla and aperture integration, Jensen, Clausen & Giménez (1988) acquired full or partial B and V light curves with $\sim$1% precisions for 6 eclipsing binaries in relatively uncrowded fields with $V_{\max}\sim14.8$–15.3. In New Zealand my collaborators and I obtained 1-3% precisions in B, V and I using a 0.6-m telescope and relatively simple observational and PSF-fitting techniques on 5 stars with $V\sim14.3$–15.7 (see Tobin 1994 for a review and references). Numerous improvements to technique and a 1-m telescope have resulted in precisions below 1% even for an object where subtraction of the light from adjacent stars has been essential (HV 982, $V\sim14.6$, Pritchard, Tobin & Clark 1994). Light curves of the requisite quality are clearly achievable using relatively-modest telescopes and appropriate care.

To date, radial velocities have proved more problematical. Andersen (1991) estimates that some 25 points on each curve with a real individual uncertainty of $\sim\pm1$ km s^{-1} should suffice. Velocities of this accuracy cannot be obtained from the broad hydrogen or helium lines. Niemela and coworkers (1986, 1994) have published velocities for some bright systems ($V_{\max}\sim12.4$–14.3) primarily derived from HI, HeI and HeII lines recorded with a 1-m telescope and image tube or photon-counting system at CTIO. Errors per velocity point range from 12 to 52 km s^{-1}. The 3.9-m AAT, RGO spectrograph and a CCD detector at Siding Spring unfortunately produced no better results for two of Jensen *et al.*'s 15th-magnitude stars, despite use of cross-correlation analysis (Bell *et al.* 1991, 1993). This was perhaps partly because it was still necessary to include lines of HeI in the cross correlation. The difficulty, of course, is that in the optical the metal lines are weak for early-type stars, and weaker yet in the low-metallicity Clouds.

On a brighter note, however, better data is being secured by Clausen and collaborators (Copenhagen) using the 3.5-m NTT at ESO. While the S/N ratio is $\sim$25, the spectral resolution is $\sim$0.5Å over a large spectral range (340 nm). Metal lines are stronger in the uv so calibrated uv spectra should simultaneously yield velocities and the flux distributions important for distance determinations (see below). Guinan (Villanova) has been awarded HST time to try this.

Table 1. SMC distance modulus error budget

QUANTITY	UNCERTAINTY	CONTRIBUTION TO TOTAL ERROR FOR 15-20 kK	25-30 kK
f_V	±2%	∓0.034	∓0.056
$f_{143\,\mathrm{nm}}$	±5%	±0.030	±0.061
R	±2%	±0.043	±0.043
$E^{\mathrm{MW}}_{\mathrm{B-V}}$	$\pm0.02^{\mathrm{mag}}$	∓0.002	±0.024
$E^{\mathrm{SMC}}_{\mathrm{B-V}}$	$\pm0.02^{\mathrm{mag}}$	±0.027	±0.083
	TOTAL:	±0.068	±0.123

Obtaining radial-velocity curves will be easier once 8-m telescopes are available in the southern hemisphere. But one may anticipate that stars fainter than $V\simeq16.0$ will still be unreachable. Microlensing surveys are mostly concerned with the more numerous faint stars, but to be useful for eclipsing-binary work (and variable-star astrophysics generally) bright objects must also be included. (The aforementioned EROS catalogue contains no stars brighter than $V\simeq15.0$ because none are in the parent database.)

Absolute photometry is required if eclipsing binaries are to be used as primary distance indicators. Discussions of the method have written the distance modulus as

$$\begin{aligned}(m_V-M_V)_0 &= m_V-A_V-M_{\mathrm{bol},\odot}+5\log(R/R_\odot)\\ &\quad+10\log(T_{\mathrm{eff}}/T_{\mathrm{eff},\odot})+BC\end{aligned}$$

(e.g. Giménez *et al.* 1994). This equation applies to each star individually, and can be adapted to apply to the system. However the physics of the method and the error budget are more apparent if one writes

$$\begin{aligned}(m_V-M_V)_0 &= -2.5\log(f_V)-A_V+5\log(R/\mathrm{pc})\\ &\quad+2.5\log(F_V)-5,\end{aligned}$$

where f_V is the observed monochromatic flux at Earth at the wavelenth of the V filter and F_V is the corresponding flux at the stellar surface. The effective temperature, *per se*, is not needed; what is needed is a model atmosphere that correctly predicts F_V. For this, as much of the total flux as possible must be observed. Since most of the flux is radiated in the uv, uv spectrophotometry is essential for the accurate estimation of F_V, which derives from model atmospheres and flux fitting. For the error budget, determining F_V is essentially equivalent to interpreting, say, the observed $(f_{143\,\mathrm{nm}}/f_V)$ flux ratio, which must be corrected for interstellar extinction. Table 1, which summarizes the error budget for the SMC (the LMC is slightly better), shows that distances should be determinable to better than 5%, so long as the hottest systems are avoided.

IV. APSIDAL MOTION

Eclipsing binaries exhibiting apsidal motion are especially interesting because the apsidal constants depend not only on the radii of the stars (an external property), but also on their internal distribution of mass, and so offer the possibility of deeper tests of structure models. Since the apsidal period $U \propto R^5$, a prerequisite is an accurate solution from the light and velocity curves. At present two systems are known that show apsidal motion: HV 2274 (P=5.73 d, U=123±3 yr, Watson *et al.* 1992) and HV 982 (P=5.34 d, $U\sim$190 yr, Pritchard *et al.* 1994). Published Harvard photographic timings were crucial for determining the apsidal rates.

V. PRESENTLY-ANALYZED SYSTEMS

Some systems have been analyzed on the basis of light or velocity curves only (e.g. Niemela & Morrell 1986; Davidge 1987, 1988; Loudon & Budding 1993; Niemela & Bassino 1994). The lack of velocity curves can be overcome by *assuming* a distance and theoretical or empirical mass-radius-luminosity relationships. This approach is being applied to the EROS stars (e.g. Pritchard *et al.* 1996) and has shown that HV 12634, if in the LMC, is either too hot and/or too small compared to average Galactic main-sequence stars (West, Tobin & Gilmore 1992). In a similar vein, Claret (1996) has used the apsidal motion of HV 2274 to estimate component masses.

The only two sytems so far analyzed on the basis of velocity *and* high-quality light curves are HV 2226 in the SMC and HV 5936 in the LMC (Bell *et al.* 1991, 1993). Both systems are post-mass-transfer, semi-detached systems.

VI. FUTURE PROSPECTS

The two most promising systems as distance indicators and for tests of low-metallicity stellar models are HV 982 and HV 2274. Both are bright, detached and show apsidal motion, and definitive analyses can be expected within the next few years. However both are in the LMC. There is no system that is as promising among the known eclipsing binaries in the SMC. May some be uncovered by the microlensing surveys!

Over 60 eclipsing binaries are known in M31. Their use as distance indicators will be challenging since the distance modulus is 6 mag. greater than for the LMC.

REFERENCES

Andersen J., 1991, A&A Rev., 3, 91
Bell S.A. *et al.*, 1991, MNRAS, 250, 199
Bell S.A. *et al.*, 1993, MNRAS, 265, 1047
Butler C.J., 1978, A&AS, 32, 83
Charbonnel C. em et al., 1993, A&AS, 101, 415
Claret A., 1996, A&A (in press)
Claret A. & Giménez A., 1992, A&AS, 96, 255
Claret A. & Giménez A., 1995, A&AS, 114 549
Cook K.H. *et al.*, 1995, in *Astrophysical Applications of Stellar Pulsation,* Stobie R.S. & Whitelock P.A. (Eds), ASP Conf. Ser., 83, 221
Dartayet M. & Dessy J.L., 1952, ApJ, 115, 279
Davidge T.J., 1987, AJ, 94, 1169
Davidge T.J., 1988, AJ, 95, 731
Gaposchkin S., 1965, Kl. Veröff. Remeis-Sternw. Bamberg, 4, Nr. 40, 66
Gaposhkin S.I., 1970, SAO Sp. Rep. No. 310
Gaposhkin S., 1977, SAO Sp. Rep. No. 380
Giménez A. *et al.*, 1994, Exper. Astron., 5, 181
Grison P. *et al.*, 1995, A&AS, 109, 447
Jensen K.S., Clausen J.V. & Giménez A., 1988, A&AS, 74, 331
Kurucz R., 1993, in *Light Curve Modeling of Eclipsing Binary Stars* Milone E.F. (Ed) p. 7, Springer-Verlag
Leavitt H.S., 1908, Ann. Harvard Coll. Obs., 60, 87
Loudon M. & Budding E., 1993, Ap&SS, 201, 287
Niemela V.S. & Morrell N.I., 1986, ApJ, 310, 715
Niemela V.S. & Bassino L.P., 1994, ApJ, 437, 332
Payne-Gaposchkin C.H. 1971, Smithson. Contr. Astrophys., No. 13
Payne-Gaposchkin C. & Gaposchkin S., 1966, Smithson. Contr. Astrophys., No. 9
Pritchard J.D., Tobin W., Clark, M., 1994, Exper. Astron., 5, 43
Pritchard J.D. *et al.*, 1996, in *Third Pacific-Rim Conference on Progress on Close Binaries,* ASP Conf. Ser. (in press)
Schaerer D. *et al.*, 1993, A&AS, 98, 523
Shapley H. & McKibben V., 1942, Bull. Harvard Coll. Obs., No. 916, 19
Shapley H. & McKibben Nail V., 1952, Proc. Nat. Acad. Sci., 39, 1
Tobin W., 1994, Exper. Astron., 5, 67
Watson R.D. *et al.*, 1992, MNRAS, 258, 527
West S.R.D., Tobin W., Gilmore, A.C., 1992, MNRAS, 254, 419