5. STELLAR MASSES AND SURFACE GRAVITIES

PRECISE STELLAR MASS AND MASS-LUMINOSITY DATA

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Abstract. Recent progress in observing and data reduction methods for precise mass and mass-luminosity determinations in binary systems are briefly reviewed. The foundations appear to have been laid for a new burst of accurate data. Detailed model simulations of the individual systems are the best way to use these data to critically test the theoretical models and advance our understanding of the evolution of single and binary stars.

1. Introduction

Second in importance only to its actual existence (Maeder, this meeting!), the *mass* of a star is its most fundamental physical property, and its apparent luminosity is usually the parameter first observed. Similarly, stellar models are usually specified primarily by their initial mass, and their luminosity is computed so as to allow comparison with the real stars. Because luminosity, like most other observable stellar properties, depends very sensitively on mass, great accuracy is required of empirical data that are to be used in tests of theoretical models.

Precise stellar mass and radius determinations, including the techniques, available data, and their interpretation, were reviewed in detail a few years ago (Andersen, 1991). Here, we recall some of the uses of these data and the accuracies required for various purposes, review recent improvements in the techniques for precise mass and mass-luminosity determinations, and illustrate some recent applications. To avoid duplication, this review will be limited to stars more massive than ~0.75 $M_{\odot}$, while stars below this limit are reviewed in the following paper by M. Mayor.

T.R. Bedding et al. (eds.),
Fundamental Stellar Properties: The Interaction between Observation and Theory, 99–108.

2. Needs for Precise Stellar Mass and Mass-Luminosity Data

Accurate, fundamental stellar mass and mass-luminosity data can be derived only from precise studies of stars in binary systems. Suitable systems must be selected so as to yield accurate results for the individual stars, and only data from non-interacting systems can be expected to be valid for normal, single stars.

The data are used in a variety of studies in galactic and stellar astronomy. In galactic astronomy, applications include:

- Binary stars with well-determined radii and effective temperatures, hence luminosities, can be used as distance indicators within the Milky Way and to nearby galaxies (see, e.g., Bell et al. 1991, 1993), mass being essentially a by-product in this context.
- Data for well-defined stellar types can be used to estimate the total mass of the components of our own and other galaxies (halo, bulge, disk).
- Similarly, accurate mass-luminosity data are needed when comparing the mass density in the disk as determined from an inventory of the local stars with dynamical estimates, from which the amount of any remaining dark matter follows.
- Mass-luminosity data are used to infer total masses of (open and globular) star clusters, estimating the IMF in such clusters, and assessing the degree and time scale of their dynamical evolution.
- Finally, on the border between galactic and stellar astronomy, mass and mass-luminosity data are essential in establishing ages for subgroups of stars that can define an age scale in our galaxy and help clarify the sequence of formation of its major components.

Examples of the use of precise mass and mass-luminosity data in stellar astrophysics include:

- Calibration of the fundamental properties of single stars.
- Validation of models of single-star structure and evolution.
- Study of the action of tidal forces on stellar interiors (internal rotation, rotational synchronization, orbital circularization).
- Observational constraints on models of close binary evolution.

In view of sampling and other basic uncertainties, mean errors of 5% or so in mass and/or luminosity are satisfactory for most applications in galactic astronomy. In stellar astrophysics, however, demands are stricter: Mass differences due to evolution within the main sequence for a given spectral type or colour can easily amount to $\sim$30%, while abundance variations in disk stars of the same colour and $\log g$ may correspond to mass differences of only ~5%. Accordingly, stellar masses to be used in critical tests of stellar evolution models must be accurate to ~1% or better in order to yield truly useful results (Andersen, 1991).

Fortunately, these demands can now be routinely met in suitable eclipsing or spectroscopic-interferometric binary systems using modern techniques, which will be outlined briefly in the following. It is essential to remember, however, that even the most accurate mass has no useful astrophysical application unless the nature of the star itself is specified to matching precision: Giving a number of, say, 1.500 $M_\odot$ for the mass of a given star conveys no useful information whatever if all that is otherwise known is that it is an F5 main-sequence star – a class within which actual masses vary by 30% and luminosities by factors of several. To allow meaningful interpretation, accurate masses and luminosities must be accompanied by precise indicators of age (radius or $\log g$ being the most direct and sensitive observational diagnostics) as well as chemical composition in order to derive conclusions beyond those obtainable from standard handbooks.

3. Advances in Observational Techniques

Optical interferometers may eventually yield accurate absolute rather than relative astrometric orbits for stars in binary systems. Until then, mass ratios and, thus, *individual* binary masses will continue to require accurate spectroscopic orbits for both components. These must be combined with a determination of the inclination of the orbital plane, which in eclipsing systems is done from a light-curve analysis and in non-eclipsing systems from a visual/interferometric orbit. Because the derived masses are proportional to the third power of the radial-velocity amplitudes, these are always critical for the accuracy of the result. In low-inclination systems the inclination may become equally important, however, a point worth recalling as improved interferometers bring more spectroscopic/visual binaries within reach.

3.1. PROGRESS IN SPECTROSCOPIC ANALYSIS METHODS

The accuracy of the derived spectroscopic orbital elements depends, first, on the resolution and S/N ratio of the spectra from which the radial velocities are measured. The great strides made in recent years in instrument and detector technology have also brought great advances in the quality of the spectra available for mass determinations in spectroscopic binary stars, and hence in both their accuracy and efficiency (Popper, 1993). Equally importantly, however, new data analysis techniques have been developed which considerably improve the reliability of radial velocity determinations from the blended spectra of double-lined binaries, in which no single spectral feature necessarily lends itself to a "clean" measurement of any one component. These methods fall in three basic classes:

Popper & Jeong (1994) studied the accuracy of radial velocities derived by cross-correlation of individual diffraction orders in cross-dispersed echelle spectra, and the consistency of results from different orders of the same spectrum. In continuation of earlier work by Popper & Hill (1991), they constructed synthetic double-lined binary spectra from broadened and co-added spectra of single stars to test the effect of their reduction procedures, and to derive corrections to initial radial velocities determined from simple one-dimensional cross-correlations. This basic, but powerful technique for validating the results is now generally used by all authors.

Simon & Sturm (1993) developed the so-called "disentangling" technique for double-lined spectra, somewhat analogous to the Doppler tomographic algorithm developed by Bagnuolo & Gies (1991). In the "disentangling" method one determines, by a single-value decomposition technique, the set of spectroscopic orbital elements plus two best-estimate component spectra which together yield the best overall fit to an ensemble of double-lined spectra of the system, obtained over a wide range of orbital phases. In addition to its potential for accurate orbit and mass determinations, the method has the considerable merit of yielding optimum mean, high S/N spectra of both stars. Thus, conventional model atmosphere analyses can be performed to determine individual effective temperatures and chemical compositions for the two components – key information which has previously been buried in the blended spectra. While final documentation of the performance of the method as regards the ultimate precision obtainable for the masses is still in progress, preliminary indications are very encouraging (Maxted, 1996).

A different approach is taken by Zucker & Mazeh (1994), who explicitly model the blended spectrum of a double-lined binary by a two-dimensional cross-correlation technique and develop an elegant, efficient algorithm (TODCOR) for the corresponding computations. The technique appears to work very well, even on spectra covering a short spectral range and correspondingly few lines, but care is needed with end masking of the spectra and other fine details of the cross-correlation procedure in order to avoid small residual velocity errors. Latham et al. (1996) find no significant systematic errors when applying TODCOR with optimised synthetic template spectra to the equal-component eclipsing binary DM Vir, but later experience indicates that the precaution of checking the results on a set of synthetic binary spectra constructed for an initial set of velocities – simple with today's computing power – should always be taken.

These techniques carry the promise that stellar masses can be determined with errors as low as perhaps 0.3%. At this level of accuracy, the time-honoured value 1.0385×10^{-7} for the numerical constant in the classical formula for the masses of a spectroscopic binary is actually noticeably wrong: As pointed out by Torres (1995, priv. comm.), modern values for the solar mass and astronomical unit give a value of 1.036055×10^{-7} – almost 0.2% lower than the canonical number(!) and a non-negligible difference in front-line work (Hummel et al., 1994).

Finally, in close systems, tidal deformation and mutual irradiation of the components will affect the measured radial velocities and masses to some degree. If a physical model of the binary is constructed, as routinely done for eclipsing systems, these effects can either be approximated as luminosity-weighted mean corrections to the measured radial velocities (Wilson, 1990) or directly modelled in the line profiles of a synthetic binary spectrum subjected to the same analysis as the real binary (Hill, 1993).

3.2. ADVANCES IN INTERFEROMETRY

Given accurate double-lined spectroscopic orbital elements, information on the orbital inclination is needed in order to compute absolute masses. In eclipsing binary systems, this is derived from an analysis of the light curves (see, e.g., Andersen 1991 for further references on the subject). In non-eclipsing systems, the inclination is derived from the apparent orbit on the sky as determined, with increasing accuracy, from visual, speckle, or long baseline interferometric observations. Because, again, masses are proportional to the cube of sin i and the major axis of the visual orbit, demands on accuracy are very high, and data from non-eclipsing systems have traditionally not met the selection criterion of 2% individual accuracy required for critical tests of stellar evolution models (Andersen, 1991).

However, the coming-of-age of interferometric techniques is now changing the picture. Capella (α Aur) provides a good illustration of the progress: From new spectroscopic and speckle data, Barlow et al. (1993) redetermined the masses of the components to an accuracy of $\sim$2%, with about equal contributions to the error from the two types of data. Shortly after, however, Hummel et al. (1994) determined a long baseline orbit from the Mark III interferometer which improved the accuracy of the apparent orbit by an order of magnitude (to some 0.1%) and sent the ball right back in the spectroscopists' court. Because both stars are in quite rapid evolutionary phases, knowing the masses to better than 1% does have significant impact on the precision of the astrophysical interpretation.

In spectroscopic/interferometric binaries, the orbital parallax and hence luminosity of the system result directly from the combination of absolute and angular orbital dimensions. If the luminosity ratio can be accurately established from the data, such systems yield direct anchor points on the mass-luminosity relation(s), see below. In eclipsing systems, the absolute stellar radii are first determined by combining spectroscopic and photometric orbital elements, and luminosities follow when effective temperatures can be assigned from observed colours and a suitable temperature scale; the distance of the system is a by-product, but usually only of secondary interest. Conversely, one may use effective temperatures in a spectroscopic/interferometric binary to determine absolute stellar radii from accurate observed luminosities if the angular diameters cannot, as in Capella (Hummel et al., 1994), be determined directly from the interferometric data.

Finally, we note that spectroscopic/interferometric data, even when of less than ultimate accuracy, remain valuable in special cases: While binary masses with errors of the order of 15% are not particularly useful in themselves at the present stage, an absolute distance determination to the systems themselves with an error of 5% certainly is when these systems happen, e.g., to be members of the Hyades (Torres et al., 1997).

4. The Data and Their Interpretation

Since the earlier review of accurate masses and radii (Andersen, 1991), not many new determinations in that category have been added[1]. A particular need is for more metal abundance data, a crucial parameter for the interpretation. Fig. 1 shows the basic distribution of the data in a way that highlights the fine structure of evolution (mostly) within the main-sequence band. No pretence to completeness is made, and in view of ongoing work to provide more data for cool stars (Clausen et al. 1997 and unpublished work by others), any such list would be rapidly superseded anyway. New data are included, however, for V539 Ara (Clausen, 1996), Capella (Hummel et al., 1994), DM Vir (Latham et al., 1996), RT And and GG Cyg (Popper, 1994), and CM Dra (Metcalfe et al., 1996), supplementing the previous list, primarily at lower masses.

4.1. OVERALL RELATIONS

Figs. 2 and 5 of the earlier review (Andersen, 1991) showed overall colour-mass and mass-luminosity relations for the sample; not much would be gained by repeating them here for the slightly larger sample. At first sight, these relations are deceptively tight and give the impression of a unique re-

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[1] Dr. D.M. Popper points out an unfortunate error in the entry for EW Ori B in Table 1 of Andersen (1991): The correct data are $R = 1.090 \pm 0.011 R_\odot$, $\log g = 4.426 \pm 0.010$, $\log L = 0.08 \pm 0.03$, and $M_v = 4.64 \pm 0.07$.

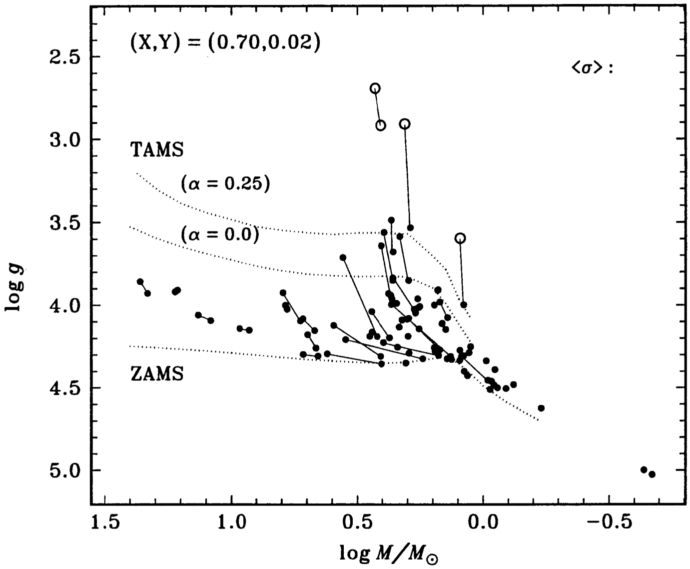

Figure 1. log M – log g diagram for binary components with individual masses and radii known to within ±2% (see text). Note that typical errors are smaller than the plotted symbols. Circles denote giant stars; lines connect members of the same system. Model boundaries are from Claret (1995).

lation with a bit of observational scatter added. And the model boundaries in Fig. 1 do generally contain the observed points. Apparently, observation and theory agree and harmony reigns.

However, difficulties set in the moment one begins to fully exploit the completeness and accuracy of the data. Stothers & Chin (1991) used model boundaries and observed binary components in the mass-radius and mass-luminosity diagrams to show that, assuming a high enough metal abundance, standard models (i.e. no overshooting) could accommodate the data. Yet, Andersen et al. (1990) showed that such overall agreement can be achieved without the models fitting individual systems satisfactorily at all. And the near-ZAMS system GG Lup is found (Andersen, 1991) to actually lie *below* the ZAMS unless a sub-solar metallicity is assumed.

A recent comparison of mass estimates from modern solar-abundance models with precise binary data (Schönberner & Harmanec, 1995) finds "remarkably good" agreement from 1.3 to 25 $M_\odot$ – again reassuring at first sight. But surely the conclusion cannot be that all stars have the same abundance? The deviations from the 45° line in their Fig. 4 are small indeed, but are they explained by the observational errors? In other words, does the diagram tell us whether or not current stellar evolution models are adequate to account for the best existing observations?

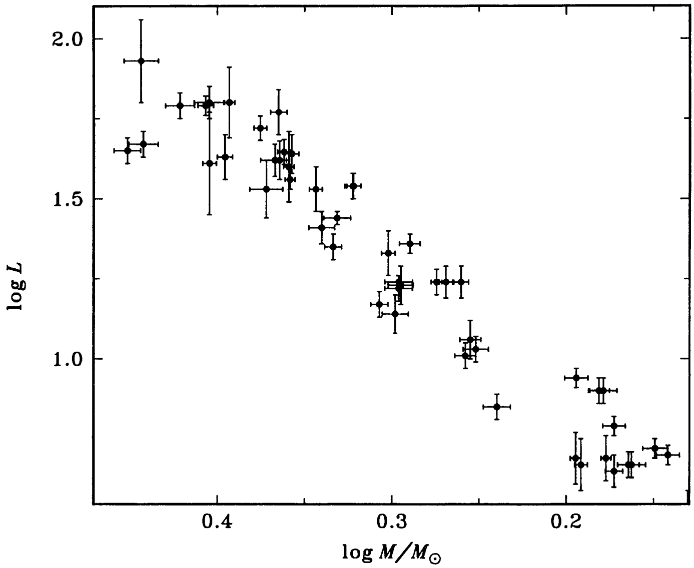

Figure 2. log M – log L diagram for a subset of the binaries in Fig. 1.

Fig. 2 illustrates the same point by zooming in on a small section of the mass-luminosity diagram. The apparently smooth overall relation obviously breaks up, and the deviation of individual stars from a mean relation are clearly significant. This is fundamentally no surprise, because the luminosity of a stellar model depends on both age and chemical composition. What Fig. 2 tells us is that, when assessing the performance of contemporary stellar models, studying average trends must be replaced by accurate modelling of individual systems, respecting all possible observational constraints.

Although published almost a decade ago, the study of the solar-type stars in AI Phe by Andersen et al. (1988) probably remains the best example of just how far one can go in the detailed modelling of a well-observed binary; but the similar studies of TZ For (Andersen et al., 1991) and Capella (Barlow et al., 1993) also yielded much useful insight into the stellar and tidal evolution of somewhat more massive stars. Much progress in the models has been made since those studies, but the number of binary systems with accurate determinations of masses, radii, luminosities *and* chemical abundances has not yet increased materially. Still, one of these few systems did provide a valuable, refined constraint on models used to fit a precise new colour-magnitude diagram of an open cluster (Nordström et al., 1997) and study the dynamical evolution of the cluster.

Most of the above examples pertain to evolutionary models for single stars, in part because accurate mass and mass-luminosity data are best determined in non-interacting binaries, and in part because of their interest for galactic and extragalactic applications. But another important reason is that the starting parameters for such models (basically mass and composition) are sufficiently few and preserved during most of a stellar lifetime that the model predictions are strongly constrained by the observations.

In contrast, processes of mass loss and mass transfer in interacting binaries may change both the masses, sizes, chemical compositions, separation, and even the apparent ages of the (refuelled) stars. As a result, starting conditions can no longer be uniquely specified, and model predictions are correspondingly poorly constrained. Nonetheless, accurate mass-luminosity data for Algol binaries have recently been used very effectively by Maxted & Hilditch (1996) to show that fundamental weaknesses still remain in current models for the evolution of Algol systems. Yet, the theory of mass exchange was thought to have solved "the Algol paradox" already some 30 years ago!

5. Conclusions

Our subject seems poised for a renaissance: New spectroscopic and interferometric tools have laid the foundations for a new burst of very accurate data on stellar masses, radii, luminosities *and* abundances, which will enhance our ability to not only test our theoretical models of stellar evolution, but also to apply the results to problems of the evolution of our own and other galaxies. Confronting the best theoretical models with all these new data, in every conceivable way, will help us ensure that we advance our understanding, not just our complacency!

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DISCUSSION

DAVID ARNETT: In your last graph, were the mass loss models done with angular momentum loss as well? Has that parameter been explored?

JOHANNES ANDERSEN: Those models did assume loss of 50% of the mass and angular momentum, but a vast parameter space remains to be explored.

TIM BEDDING: How well is mixing length constrained in these stars? Is it the same as the solar value?

JOHANNES ANDERSEN: All the single-star model series assume a mixing length around 1.5-1.6 H_p, consistent with that of the solar model in each series.