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Binarity and Stellar Evolution

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Abstract. Models of stellar evolution constitute an extremely powerful, and for the most part apparently very successful, tool for understanding the progression of a star through its lifetime as a fairly compact entity of incandescent gas. That success has led to stellar evolution theory becoming a crutch when an observer is faced with objects whose provenance or current state are in some way puzzling, but how safe a crutch? The validity of the theory is best checked by examining binary systems whose component parameters have been determined with high precision, but it can be (and needs to be) honed through the many challenges which non-conformist single stars and triple systems also present. Unfortunately the lever of observational parameters to constrain or challenge stellar evolution theory is not as powerful as it could be, because not all determinations of stellar parameters for the same systems agree to within the precisions claimed by their respective authors. What are the sources of bias—the data, the instrument or the techniques? The workshop was invited to discuss particularly challenging cases, and to attempt to identify how and where progress might be pursued.

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1. Background

The theory of stellar evolution does rather well to model and explain the changes which a star undergoes (a) from its first emergence as a celestial entity and early journey as a relative youngster on to the main sequence (of HR-Diagram language), (b) during its extended life as a hydrogen-burning star, (c) as it digs deeper for new energy sources and in so doing becomes a cooler but inflated red giant, (d) during relatively rapid vacillations as new energy sources are tapped but mass loss impoverishes it, until (e) finally it undergoes some form of explosive change, or more meekly throws in the towel, and dwindles to a state of near-permanent insignificance. In qualitative terms the sequences that are predicted seem to be borne out by observation in remarkable detail; frequently the time-scale is the only substantial feature that cannot be checked against observation.

However, when we need to compare a model prediction in actual quantitative terms we find that there can be a great shortcoming on the side of the observations, or their interpretation: how can we pin down the temperature or colour indices if we cannot also pin down the degree of reddening? Can we be sure that the assumptions underlying the derivation of surface gravity from a stellar spectrum do not bias the answers? Does overall metallicity, or an abundance-ratio anomaly, influence how we derive 'best' stellar parameters from observation? How well can we determine the mass of a single star?

In real life, stars are anything but uniform or homogeneous in their nature, behaviour and constitution. Many exhibit evidence of energy expenditure that is noticeably over and above what is required simply to exist. A-type stars pulsate, M-type stars flare, B-type stars show emission, cool giants have flickering chromospheres, etc. Does stellar-evolution theory deal in a predictive manner with those cases? If not, is it because evolution models need to be in 3-D in order to avoid smearing out local ripples, or are such effects not in fact constructive—or destructive— enough to notice on the grand scale of evolution?

Binary stars are critically important here, particularly double-lined ones, and especially if the components have quite different temperatures—as in composite-spectrum binaries. The workshop discussed some prime examples, all relatively bright stars, so most of their basic physical parameters should surely be known by now with rather high precision. But that does not seem to be the case; there are examples in the literature of disagreements in the published values for some parameters which reach as much as 10 times the σ values claimed by the respective authors.

The participants at the workshop appeared to be principally observers, but the prime representative of the theory school (Peter Eggleton) held his own remarkably well despite questions and challenges from numerous of his "opposition".

2. The Case of o Leo

An improvement in theoretical modelling was well demonstrated in the *ad hoc* recalculation of atmospheric diffusion as the cause of "metallicity" in Am and Fm stars. Since early days in the development of Michaud's diffusion theory (Michaud 1973; Michaud *et al.* 1976) it had been stated fairly categorically that diffusion could not become established below an effective temperature of about 6300 K (Vauclair & Vauclair 1982). The successful unravelling of the 4th-magnitude composite-spectrum binary o Leo, in which both components proved to have "metallic" properties and the cooler one had a T_{eff} (6100 ± 200 K) that was slightly *cooler* than the stated limit for diffusion (Griffin 2002), gave theorists a new observational fact to work with, resulting in a small modification to the mass of atmosphere involved and which had been assumed as an initial condition.

3. The Case of Capella

Although Capella is such a bright binary, its orbital parameters and the physical parameters of its component stars are not as well determined as individual authors claim. Whether or not the orbit solution includes all the historic radial velocities from the literature seems to make a difference (Branham 2008) of as much as 17% percent to the derived mass ratio. Both components are G-type giants, one somewhat cooler than the other, and the hotter one is still rotating rather rapidly—as is often typical of a "Hertzsprung-gap" giant. Measurements of the radial velocity of the secondary in the presence of a very similar but sharper-lined companion may well be affected by systematic errors which bear directly upon the derived mass ratio. Since the masses of the two giants are rather similar, uncertainties in their mass ratio become translated into serious uncertainties concerning the evolutionary status of the cooler star—in particular, whether it is on its first or later ascent of the red-giant branch.

To be specific, Weber & Strassmeier (2011) obtain a value for the hotter component's radial-velocity amplitude of 26.840 ± 0.024 km s^{-1}, while Torres *et al.* (2009) obtained 26.260 ± 0.087 km s^{-1}. Those differ by either 7 or 24σ. Until such parameters are constrained better by the observers it is difficult to apply very stringent tests to the models from which the evolutionary tracks are calculated. If this particular binary gives rise to such controversies it is fair to ask whether it is more useful in the long run to observe with high precision a small number of bright but possibly unrepresentative stars, or to rely on huge surveys yielding statistical information for faint stars only but yielding little as to how near (or how far) the statistical norm deviates from reality.

4. The Case of V 1309 Sco

Difficulties in accommodating the mass ratios and apparent evolutionary status for a number of well-studied binary systems have prompted Eggleton & Kiseleva (1996) to attribute the mis-match to a merger; such a merger might have taken place in either the current primary or the secondary component. However, until the startling behaviour of the contact binary V 1309 Sco (Nova Sco) over the past 10 years was revealed (Tylenda et al. 2011) the existence of such mergers was only postulated (though believed to be very likely nonetheless). Two outbursts in our Galaxy, V838 Mon (Munari *et al.* 2002; Bond *et al.* 2003) and V4332 Sgr (Martini *et al.* 1999) have been attributed plausibly to mergers, but the behaviour of Nova Sco which lifted it from the realms of a possible to an almost certain merger event was the rapid change of orbital period before the outburst and the disappearance of its eclipses—and indeed its orbit—afterwards; both of those are in keeping with a merger of the system's two components into one. Nevertheless, although V 1309 Sco is currently a red star (and is presumably undergoing evolution towards the giant branch right now), it does not seem to be very well agreed how cool it was before the merger. Observers are doubtless keen to monitor similar systems in the hope of finding more such events actually in progress.

5. Other Binary Systems

Good-quality parameters for detached binary systems have been compiled and published by Andersen (1991), and more recently by Torres, Andersen & Giménez (2010). However, almost all the stars listed there are dwarfs, not giants, and so do not present such an exacting challenge to stellar-evolution theory. Roger Griffin's excellent series of orbits for binary stars is also limited in that context inasmuch as almost all are for single-lined systems. To obtain a full set of stellar parameters requires in addition knowledge of a system's inclination, which is normally derived from an astrometric orbit—or can be assumed accurately enough if a system eclipses. The hope is that surveys like OGLE or MACHO will be able to return useful results for such purposes; recent results are certainly encouraging in that respect.

6. Stellar Metallicities

For many of the main-sequence binaries with well-determined physical parameters, the metallicity remains totally unknown, particularly for binaries with periods less than about 1 day. Why should that be? The metallicity is troublesome to determine when the orbital period is shorter than a few days because the accompanying rotational broadening of the lines adds serious problems of line blending. Since the location of a theoretical evolutionary track depends critically upon metallicity, the lack of that constraint obviously introduces a substantial uncertainty into the fitting of tracks to observation.

Probably the most important impact of metallicity on theoretical modelling comes from the work of Asplund *et al.* (2000, 2005), who found that the metallicity of the Sun has to be substantially revised (lowered) relative to what was the standard assumption of previous decades. This is a result of using 3-D modelling of the convective surface rather than the usual simplistic 1-D models. It has had the effect of making it much harder to match theoretically the observed and very detailed spectrum of helioseismic oscillations; agreement was very satisfactory prior to 2000. For the present (Asplund *et al.* 2010), no resolution of this conflict is in sight.

7. Conclusions

The current state of affairs offers much to encourage hope for better things to come. Several 3-D stellar-structure codes are now in operation (Asplund *et al.* 2000; Eggleton *et al.* 2006; Meakin & Arnett 2006; Stancliffe *et al.* 2011), while massive spectroscopic surveys promise to give better ideas as to the relative distributions of different stellar types and luminosities. GAIA should be a fresh source of precise physical parameters for a large number of stars.

There is probably no substitute for more and better (= more precise) data with which to test and address ongoing matters associated with theories of stellar evolution adequately and fully. However, it was not clear to the workshop whether a "broad sweep" approach (to coin a phrase from Bernard Pagel) would necessarily and incontrovertibly prove more valuable than concentrating on understanding a few bright systems better (the approach of "ultimate refinement"). Almost certainly the two approaches are complementary and not alternatives, but need to be well lubricated by improved communication. The light curves which huge new surveys for optical transients are now producing will not be beneficial in this context without some very careful calibration of the population of target objects, if such calibration is even possible. The fact that refined studies of bright stars have shown up so many oddities and oddball cases is rather depressing, inasmuch as the assumption of an "average" or "typical" stellar type or characteristic may be so gross that any theory which aspires to model such cases is likely to be rather impotent at understanding and predicting the wider range of varieties and variability which actually populate the heavens.

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