179. Stellar masses from SB2 binaries

Masses are, of course, one of the most fundamental of stellar properties, crucial in determining their structure and evolution… and everything that follows from them. Yet ways of determining accurate star masses are strictly limited and, even today, only a couple of hundred are *measured* to better than 1–2%.

The few accurate masses that are available underpin the calibration of the model-dependent methods of isochrone or stellar track fitting, which employ models of stellar structure and evolution matched to the observed star properties (e.g. Lebreton & Reese, 2020).

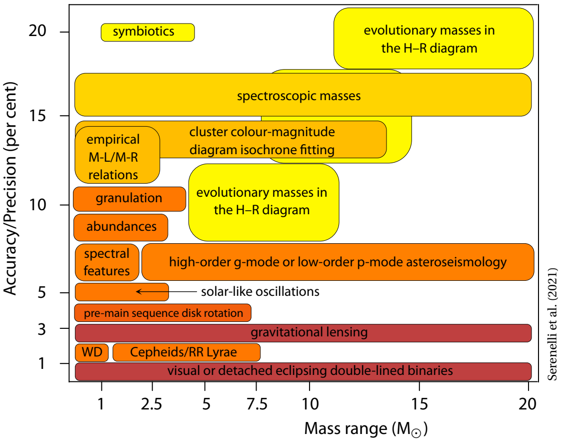
In their recent review, Serenelli et al. (2021) describe the various methods that can be used to estimate stellar masses across the Hertzsprung–Russell diagram. The most accurate, widely applicable and model-independent method employs Kepler's third law applied to detached (non-interacting) binary systems. In the absence of accurate astrometry to establish the orbit inclination, these have been mostly eclipsing systems.

Asteroseismology has opened a new, powerful, but nonetheless still model-dependent approach, while other methods can be applied to microlensed systems, or to stars in specific evolutionary stages, ranging from pre-main sequence to evolved giants and white dwarfs.

The figure shows their synopsis of these various methods, along with the applicable mass ranges and current accuracies (Serenelli et al., 2021). Methods are colour-coded, with a darker colour for increasingly model-*independent* methods, such that the darkest red regions deliver model-independent masses, which are not only precise, but importantly also *accurate*.

They list just 200 or so stars with relative mass accuracies between 0.3–2% over the mass range $0.1-16M_\odot$, 75% of which are main-sequence core H-burning, and the remainder cover all the other stages. This is somewhat better than the situation presented 30 years ago by Andersen (1991), at least in accuracy if not in number.

Here, I will look only at the most accurate (and model-independent) method of mass determination, viz. the use of double-lined spectroscopic binaries, and explain how Gaia is contributing.



Serenelli et al. (2021)

In the absence of more restricted techniques applicable to single stars (notably microlensing and asteroseismology) the determination of stellar masses relies on their gravitational effects in binary orbits, and it is useful to recall some basics.

In a non-interacting binary, each star moves in a closed elliptical orbit in inertial space, with the centre of mass at one focus. Such a Keplerian orbit in three dimensions is described by 7 parameters: $a, e, P, t_\mathrm{p}, i, \Omega, \omega$, where a and e specify the size and shape of the orbit, P is related to a and the component masses through Kepler's third law, and t_p is the position of the object along its orbit at a particular reference time. The three angles (i, Ω, ω) represent the projection of the true orbit into the observed (apparent) orbit; they depend solely on the orientation of the observer with respect to the orbit.

For single-lined spectroscopic binaries, in which only one star's spectrum is seen, radial velocity measures provide the mass function, $f = (M_2 \sin i)^3/(M_1 + M_2)^2$. For double-lined spectroscopic binaries (i.e. with two distinct spectra), the mass function for both can be established, and hence the mass ratio, but still neither the individual masses, nor the orbit inclination.

From radial velocities alone, masses can only be determined unambiguously if the system is eclipsing, imposing an explicit value for the inclination, viz. $i \simeq 0$.

Eclipsing systems, of course, represent only a small subset of all binaries, and bias inferences to shorter periods. They can, in turn, be affected by mutual interactions including tidal distortion and mass transfer, so that only a minority of eclipsing binary components are truly representative of single stars (e.g. Popper, 1967).

The addition of astrometric measurements changes prospects significantly, because all seven orbit elements become accessible in principle. In practice, different considerations apply according to whether the system is a 'visual binary' or an unresolved 'astrometric binary', whether the measurements probe all or part of the orbital motion of one or both components, or only that of the photocentre, and whether the orbital solutions also take account of constraints from radial velocity data (e.g., Torres, 2004; Anguita-Aguero et al., 2022).

For example, an orbit solution from the astrometry of (resolved) visual binaries yields the orbit inclination, and hence individual masses (e.g. Serenelli et al., 2021, §2.3). Suitable astrometric measurements have not been easily obtained in the past, often calling for speckle or interferometric measurements over many years.

Over its 3-year mission, Hipparcos provided just 235 orbital solutions for unresolved astrometric binaries (Lindegren et al., 1997), of which mass ratios could be obtained for about 25 (Söderhjelm, 1999).

With that background, let me summarise the progress in mass determinations over the past four decades as exemplified by four major reviews.

Popper (1980) gave masses for about 100 eclipsing and visual binary components known to better than 20% (requiring parallaxes to better than 7%). He commented that *'It is rather sad, in view of the very great amount of difficult observing for more than 150 years, that the number of visual binaries for which masses are known to an accuracy of about 20% is not more than a dozen or so.'*

Andersen (1991) gave masses, again better than 20%, for just 45 detached double-lined eclipsing binary systems (90 single stars), covering spectral types O8–M1 on the main sequence, and with two red giants. Compared to Popper (1980), data for only 6 systems remained unchanged; improved data were given for 18 systems, and 21 systems were new additions.

Torres et al. (2010) listed 95 detached binaries containing 190 stars (comprising 94 eclipsing systems, and the astrometric binary α Cen) for which masses *and* radii were estimated to better than 2–3%, along with 23 other systems with accurate masses but less accurate radii. Their sample more than doubled that of Andersen (1991), and extended the mass range to $0.2-30 M_\odot$.

Serenelli et al. (2021) provide the most recent review of mass-determination methods. Their resulting compilation includes masses for 40 detached eclipsing binaries (80 stars) better than 2% (their Table 2), and for 36 visual binaries (72 stars) better than 3% (their Table 3).

Now to Gaia, where the binary and multiple star processing is highly complex, dependent on the wide range of systems (orbital period, magnitude difference, variability, etc.), and on the various combinations of data that can be used in the orbit solution (astrometry, photometry, and RVS velocities). Arenou et al. (2023) identified 800 000 binaries in DR3 with orbit or trend parameters, classified as astrometric, spectroscopic, and eclipsing, in various combinations (their Table 1).

Of these, 165 500 are astrometric solutions characterising the orbit of the *photocentre*, yielding the system's parallax and proper motion, the orbit inclination and its standard error (Halbwachs et al., 2023c, Eqs A6 and A20), and the 'astrometric mass function', which depends on the component fluxes, F_1 and F_2 (Arenou et al., 2023 Eq. 2; Halbwachs et al., 2023c Eq. 14). Again, the degeneracies can be broken for eclipsing binaries, or for double-lined (SB2) spectroscopic binaries.

I am not aware of any synthesis of the best masses available from DR3, but results include several astrometric orbits with $\sin^3 i$ better than 1%, with the best masses at the level of around 0.3% (Halbwachs et al., 2023b).

Radial velocities from Gaia's RVS spectrometer are not at the accuracies required for the best mass determinations, and state-of-the-art masses exploiting the Gaia data still largely also rely on ground-based radial velocity measurements. Thus Chevalier et al. (2023) combined DR3 astrometry with SB2 data from the Ninth Catalogue of Spectroscopic Binary Orbits (SB9), and APOGEE, to determine masses for 56 systems (43 from SB9, and 13 from APOGEE), and provided an empirical mass–luminosity relation down to $0.12 M_\odot$.

Similarly, ground-based campaigns are ongoing to acquire radial velocities (along with interferometric or speckle data in some cases) targetting masses at 1% accuracy when eventually combined with future Gaia astrometry. Amongst these are 70 binaries being observed with OHP–SOPHIE (Halbwachs et al., 2014; Kiefer et al., 2016; Halbwachs et al., 2020), and the follow-up of other suspected SB2s from Gaia (Halbwachs et al., 2023a).

Other works are using these fundamental masses, combined with theoretical stellar evolution models, to estimate stellar masses from observed luminosities, based on Gaia G-band magnitudes and stellar distances (e.g. Lebreton & Reese, 2020; Malkov et al., 2022; Chevalier et al., 2023; Eker et al., 2024; Pérez-Couto et al., 2024).

To my knowledge, no results have been published yet from Gaia's resolved orbital binaries, for which masses should also be available, although I have no feeling for the numbers of objects involved. Data Release 4, in 2025, will also cover a longer time interval, and will include astrometry at each measurement epoch. Again, I can offer no useful insight into the expected state of stellar mass determination at the end of the Gaia mission.