

Combined Spectroscopic and Interferometric Orbits for HD 193322

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Abstract: The star HD 193322 is a remarkable multiple system that lies at the heart of the cluster Collinder 419. Here we report on a new spectroscopic orbit for the central binary ($P = 312$ d) based on spectra collected over the last decade. We have also obtained long baseline interferometry of the target in the K' -band with the CHARA Array, and the fringe packet from the nearby companion was used to calibrate the visibility of the fringes of the shorter period binary. We performed an analysis of the fringe visibilities from many epochs, position angles, and baselines to obtain an astrometric orbit for the inner binary. We discuss the masses and other properties of the binary from the combined spectroscopic and astrometric results.

1 Introduction

The massive O-type stars are usually found with one or more nearby companions (Mason et al. 2009). Most of these luminous stars are very distant, and consequently, we generally only detect their very nearby companions (through Doppler shifts) or very distant acquaintances (angularly resolved). We must rely on high angular resolution observations of the few nearby cases to detect those elusive, mid-range separation, binary stars. One of the most revealing examples is HD 193322 (O9 V:(n); Walborn 1972), the central star in the sparse open cluster Collinder 419. The distance to the cluster is 741 ± 36 pc according to the recent study by Roberts et al. (2010). The first hint of the star's multiplicity came with the discovery of a companion Ab through speckle interferometry observations by McAlister et al. (1987), and subsequent speckle measurements detected its orbital motion (Hartkopf et al. 1993). The optical spectrum is dominated by a relatively narrow-lined component Ab1, and Fullerton (1990) discovered significant radial velocity variations in this component indicative of a spectroscopic binary. The first spectroscopic orbit for Ab1 was presented by McKibben et al. (1998), who determined an orbital period of 311 d. In addition to the close Ab spectroscopic pair and the speckle Aa,Ab pair, there is another wider companion B at an angular separation of 2.6 arcsec. A mobile diagram presenting the known components of this multiple system is illustrated in Figure 1.

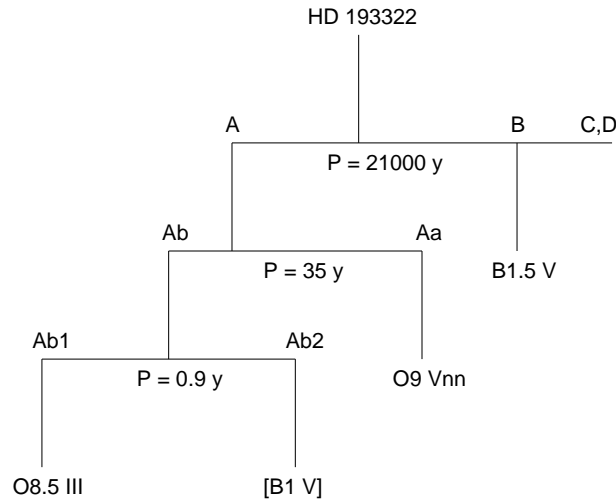


Figure 1: A mobile diagram of the components of the multiple star HD 193322.

2 Resolved Astrometric Orbits

The orbital motion of the Aa-Ab pair has been followed since its discovery by Mason and Hartkopf (USNO) through continued speckle interferometry observations (Mason et al. 2009) and new separated fringe packet observations with the CHARA Array long baseline interferometer (Farrington et al. 2010). The CHARA Array is an optical/infrared system consisting of six 1 m aperture telescopes in a Y-shaped configuration with baseline separations of 30 to 330 m (ten Brummelaar et al. 2005). We observed HD 193322 with the CHARA “Classic” beam combiner in the near-IR K' -band using a variety of telescope pairs over the period from 2005 to 2010. These observations always separated the Aa and Ab fringe packets of the speckle binary, and in the best circumstances we were able to measure the projected separation for several, near-orthogonal baselines. These were combined to obtain the separation and position angle of the Aa,Ab pair (see details of the method in Farrington et al. 2010). Mason and Hartkopf (priv. communication) have made a new orbital solution based on the full data set that is illustrated in Figure 2. The orbital period is 34 y, and using the cluster distance from Roberts et al. (2010), the period and semimajor axis yield a total mass (of Aa, Ab1, and Ab2) of $59 \pm 13M_{\odot}$.

The interferometric visibility of a very close binary is modulated as a sinusoid with increasing baseline, where the cycle length is related to the projected separation on the sky (Raghavan et al. 2009). The calibration of visibility is aided when the signal of a nearby star produces a separated fringe packet that can be used to calibrate the visibility of the central binary. We have used this self-calibration method with the set of CHARA Array observations of HD 193322. We fit these calibrated visibilities with a relative orbit for Ab1,Ab2 by performing a grid search for the semimajor axis, inclination, longitude of the ascending node, and the magnitude differences of the Aa,Ab and Ab1,Ab2 pairs (the orbital period and epoch were set from the spectroscopic results for the circular orbit of Ab1; see §3). The preliminary solution for the angular orbit of Ab1,Ab2 is shown in Figure 3. Again adopting the distance from Roberts et al. (2010), the derived total mass of the Ab1,Ab2 pair is $43 \pm 7M_{\odot}$. The difference in the mass sums for the Aa,Ab and Ab1,Ab2 orbits yields an approximate mass estimate of Aa of $15M_{\odot}$, which is close to the nominal mass of $17M_{\odot}$ for a typical O9 V star

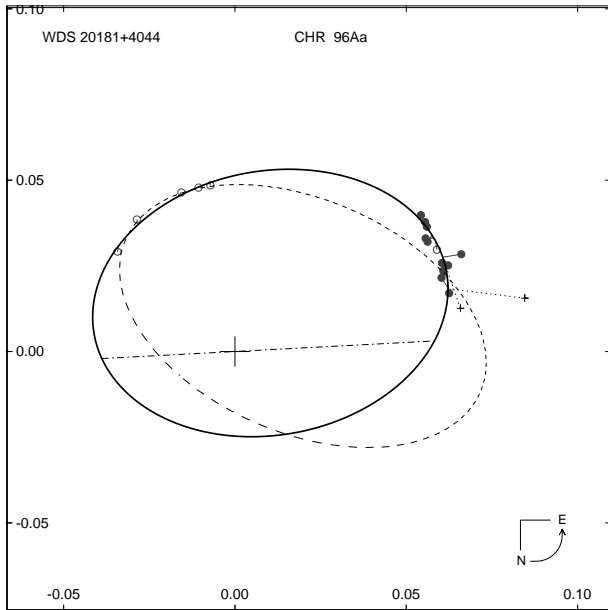


Figure 2: The astrometric orbit of the Aa,Ab pair (in units of arcsec). The dashed curve represents the first solution (Hartkopf et al. 1993) while the solid curve is the new solution from Mason and Hartkopf. The dot-dash line shows the line of the nodes. The filled circles represent the CHARA Array separated fringe packet results. The reliable speckle observations are displayed as open circles, while the poorer speckle points are zero weighted and are shown as plus signs connected to the calculated positions by dashed $O - C$ lines. Note that north is down and east to the right in this figure, and the directional arc in the lower right corner shows the counter-clockwise sense of orbital motion.

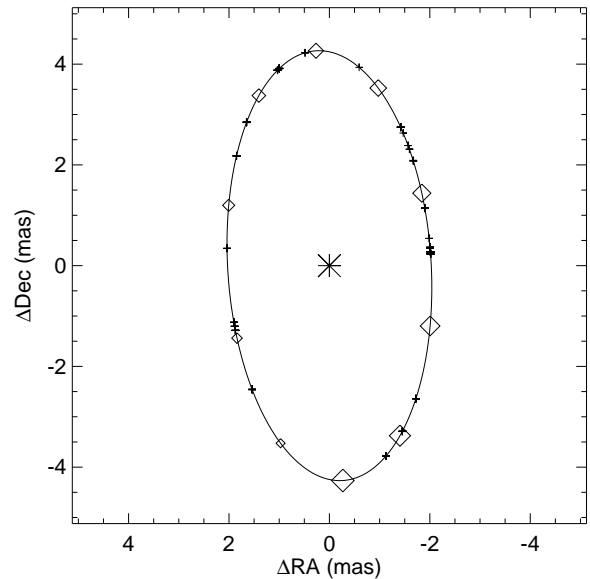


Figure 3: The astrometric orbit of the Ab1,Ab2 pair (in units of milli-arcsec = mas) based upon new CHARA Array visibility measurements. The sense of the orbit progresses counter-clockwise from the largest diamond (at the crossing of the ascending node of Ab1) through smaller symbols for steps of $0.1P$. Plus signs indicate the calculated positions at the times of observation. Note the much smaller angular scale and the different orientation compared to the Aa,Ab orbit shown in Figure 2.

(Martins et al. 2005). This suggests that Aa consists of only one star as indicated in Figure 1.

3 Spectroscopic Orbit

Spectroscopy potentially holds the key to determine the mass ratio of the Ab1,Ab2 pair, and hence, to find the masses of all three of the central stars. Furthermore, the spectral lines associated with each component can help us determine the temperature and relative flux of each star. This is a difficult task, however, because the stars are so close that conventional, ground-based spectroscopy will record the flux of all three stars (as well as the flux of component B in many cases) and because their Doppler shifts are comparable to the line widths so that line blending is severe. Nevertheless, we have started this task by analyzing a set of new moderate and high dispersion optical spectra of HD 193322. Most of these spectra were obtained with the Kitt Peak National Observatory 0.9 m coudé feed telescope, with resolving powers around $R = 10000$. This set was augmented with several higher resolving power spectra ($R = 75000$) from the Canada-France-Hawaii Telescope and ESPaDOnS spectrograph and the Nordic Optical Telescope and FIES spectrograph. We show an example of the CFHT spectra

in Figure 4. We focus here on the spectrum of Ab1 that is a major flux source, has narrow spectral lines, and displays Doppler shifts over the shorter orbit of Ab1,Ab2. The spectral lines of the narrow-lined component are consistent with those of a hot star ($T_{\text{eff}} \approx 33$ kK) that contributes about 40% of the optical flux. There is also a very broad-lined component that contributes about the same flux fraction. This component does not participate in the short period orbital motion of Ab1,Ab2, but does show the long term variation expected for the Aa component. The much fainter Ab2 and B components account for the remaining flux.

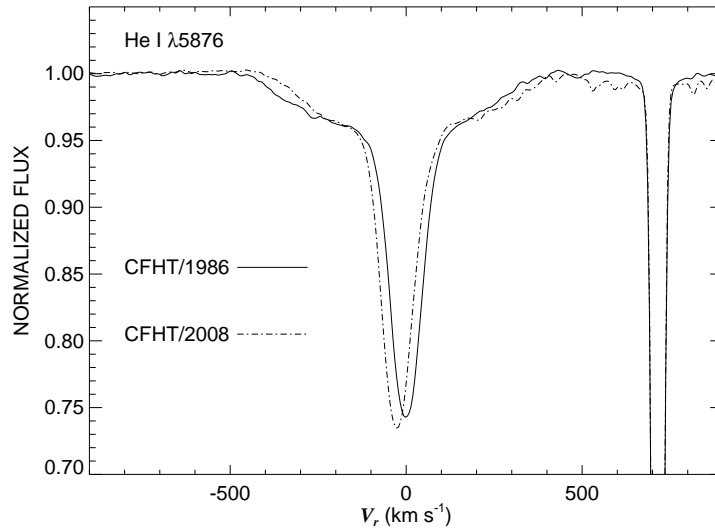


Figure 4: CFHT spectroscopy of the He I $\lambda 5876$ line profile from two epochs. The narrow-lined component is associated with Ab1, while the broad-lined component corresponds to Aa.

Since the Ab1 component is so dominant in the spectrum, it is relatively straight forward to measure its orbital Doppler shifts. We measured radial velocities by cross-correlating the observed spectra with a model absorption line spectrum for Ab1 (from the grid of Lanz & Hubeny 2003). The velocities of Ab1 must be adjusted for the motion of the Ab1,Ab2 center of mass in the orbit of Aa,Ab (which depends on the mass ratios). We made this correction by an iterative method to determine the orbital motion of Ab1 in both the short and long period binaries. This was done by fitting the residuals from the short period orbit with the period P , eccentricity e , and longitude of periastron ω fixed from the astrometric orbit for the long period binary Aa,Ab, and with the systemic velocity γ , semiamplitude K , and epoch of periastron T as parameters to be determined. The resulting solution of the long period orbit was then used to correct the observed velocities for motion in the wide orbit, and a new solution was found for the short period orbit. This procedure quickly converged to the orbital solution shown in Figure 5 (for a circular orbit).

These kinds of observations hold significant promise for the determination of the masses and dynamical evolution of this remarkable multiple star system. For example, the semiamplitude of the spectroscopic orbit of Ab1 can be combined with the semimajor axis and inclination from the angular orbit and with the distance from the cluster to estimate the mass ratio of the Ab1,Ab2 pair and, hence, their individual masses. Furthermore, continuing high resolving power spectroscopy will yield an accurate, double-lined orbit for the Aa,Ab pair to provide an independent estimate of their masses. Once reliable orbital solutions are known, Doppler tomography reconstructions of the spectra will help us assign the other physical parameters of the stars. These data will shed light on the dynamical formation processes of massive, multiple star systems like HD 193322 that are often found at the centers of dense clusters.

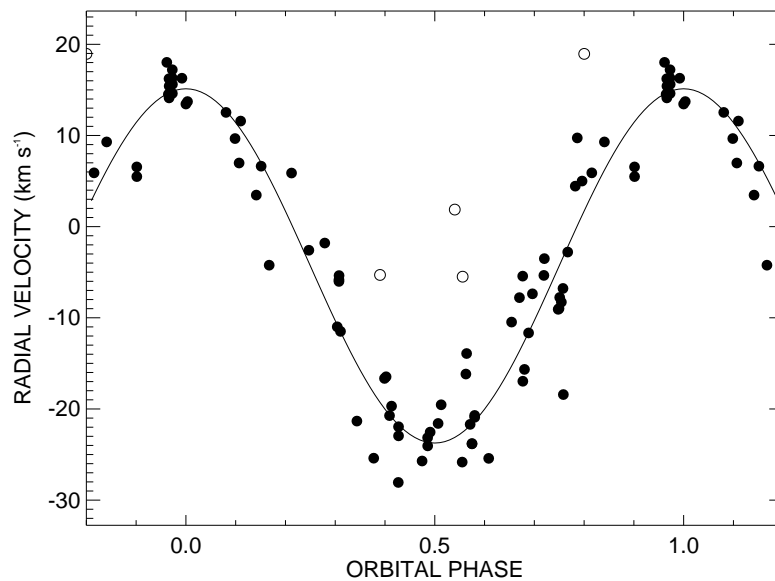


Figure 5: The derived radial velocity curve of Ab1 (solid line) in the 312 d orbit based upon the corrected radial velocity measurements. Open circles indicate those measurements assigned zero weight in the solution. Phase zero corresponds to the time of maximum radial velocity (star crossing the ascending node) in this circular orbit.

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