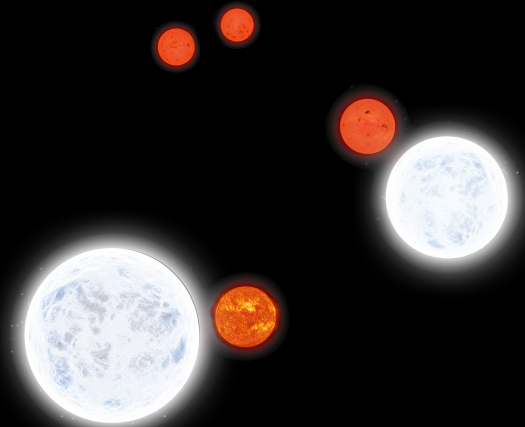


The Sextuple System of Castor: Orbits and Dynamical Masses

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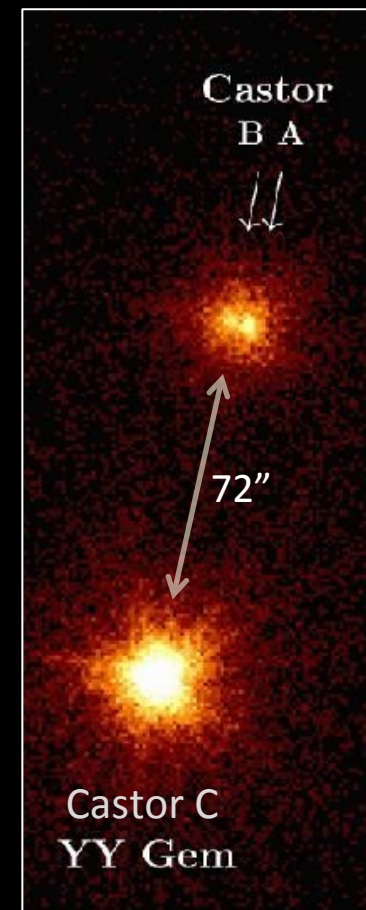
- Castor (α Gem): a well known bright ($V = 1.58$), nearby (15 pc) visual binary system with an orbital period of about 450 yr (current separation 5.5")
 - Discovered in 1718, if not earlier (Cassini 1678?)

Phil. Trans. Roy. Soc. London, 72, 112 (1782)

XII. *Catalogue of Double Stars. By Mr. Herschel, F. R. S. communicated by Dr. Watson, Jun.*

Read January 10, 1782.

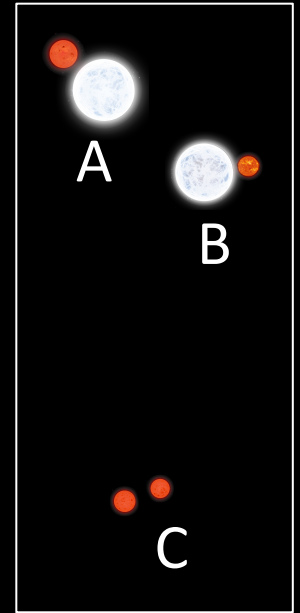
i. \dagger α Geminorum, FL. 66. In capite præcedentis II
 April 8, Double. A little unequal. Both w. The vacancy
 1778. between the two stars, with a power of 146, is 1 diameter of S.; with 222, a little more than 1 diameter of L.; with 227, $1\frac{1}{2}$ diameter of S.; with 460, near 2 diameters of L.; (see fig. 6.) with 754, 2 diameters of L.; with 932, full 2 diameters of L.; with 1536 (very fine and distinct) 3 diameters of L.; with 3168, the interval extremely large, and still pretty distinct. Distance by the micrometer $5''$, 156. Position $32^{\circ} 47'$ n. preceding. These are all a mean of the last two years observations, except the first with 146.



X-ray image, ESA

- First true physical binary to be recognized as such, by William Herschel (1803), from changes in the position angle over four decades

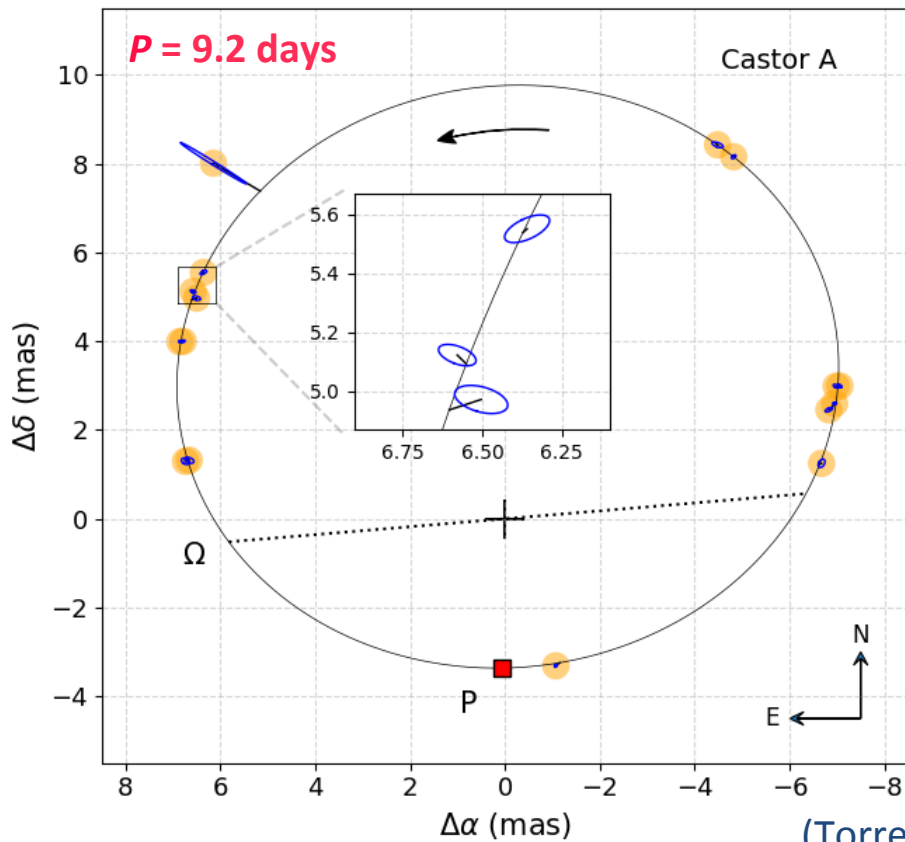
- *Sextuple* system: Castor A, B, C, each a binary
 - Castor A: SB1, $P = 9.2$ days (Curtis 1906)
 - Castor B: SB1, $P = 2.9$ days (Belopolsky 1897)
 - Castor C: SB2, eclipsing (YY Gem), $P = 0.81$ days



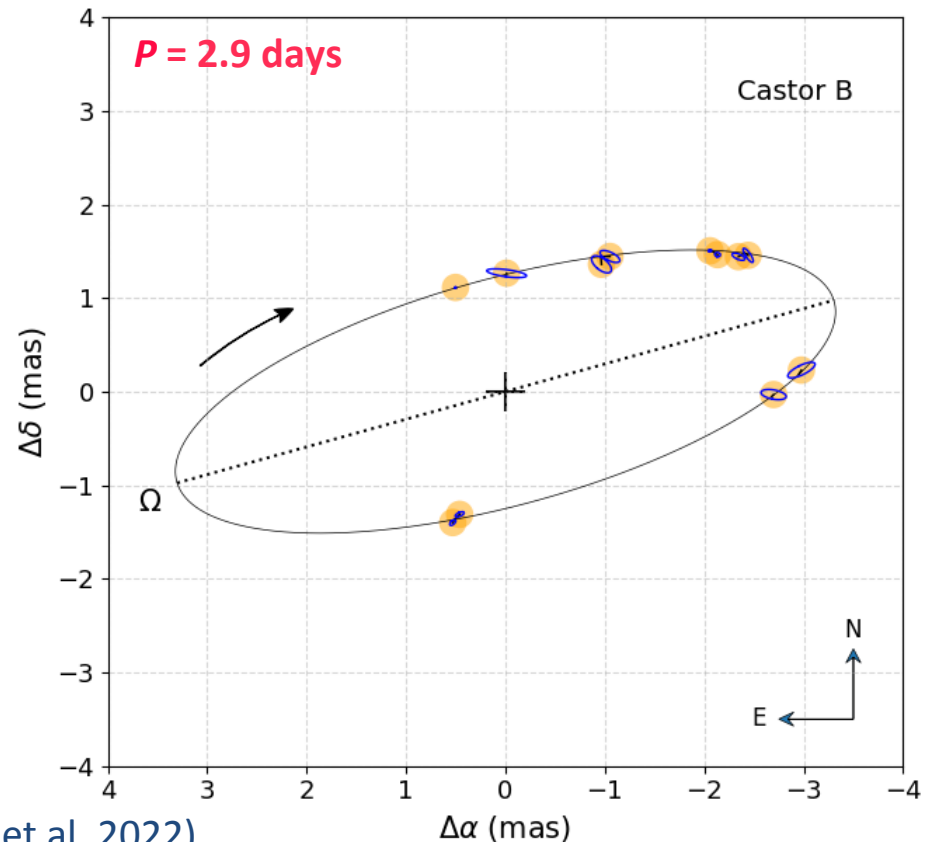
- Castor A and B never spatially resolved before, despite being very bright objects ($H = 1.3$ and 3.0)
 - Archival MIRC observations of Castor A from 2007
 - NOIRLab proposals

Castor A and B resolved with the CHARA Array

- Reobserved in 2021 March, November, December
- Near infrared beam combiners (MIRC-X, MYSTIC): H and K bands
- Companions are *very* faint: 0.5% (Ab) and 1% (Bb) of the primary flux in H

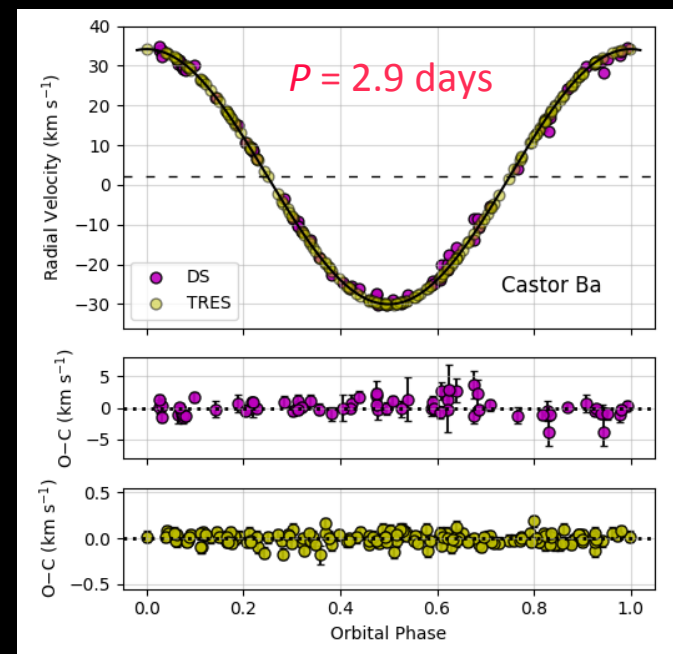
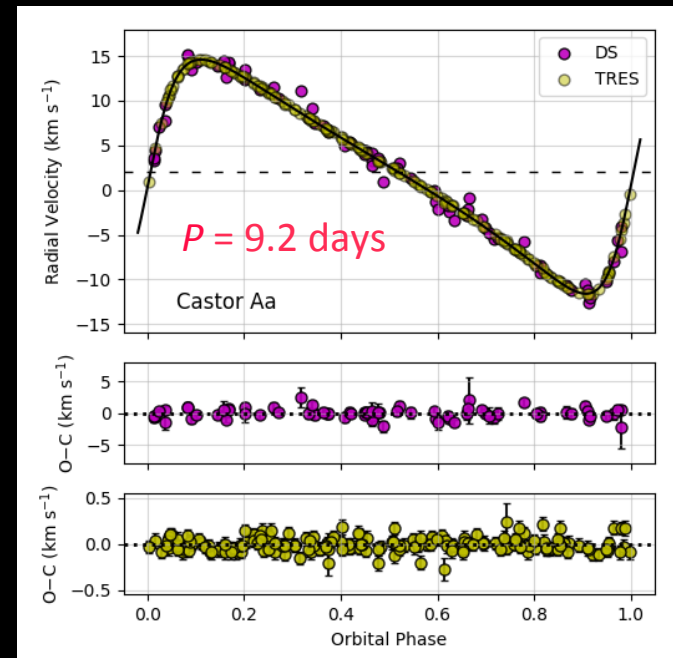


(Torres et al. 2022)

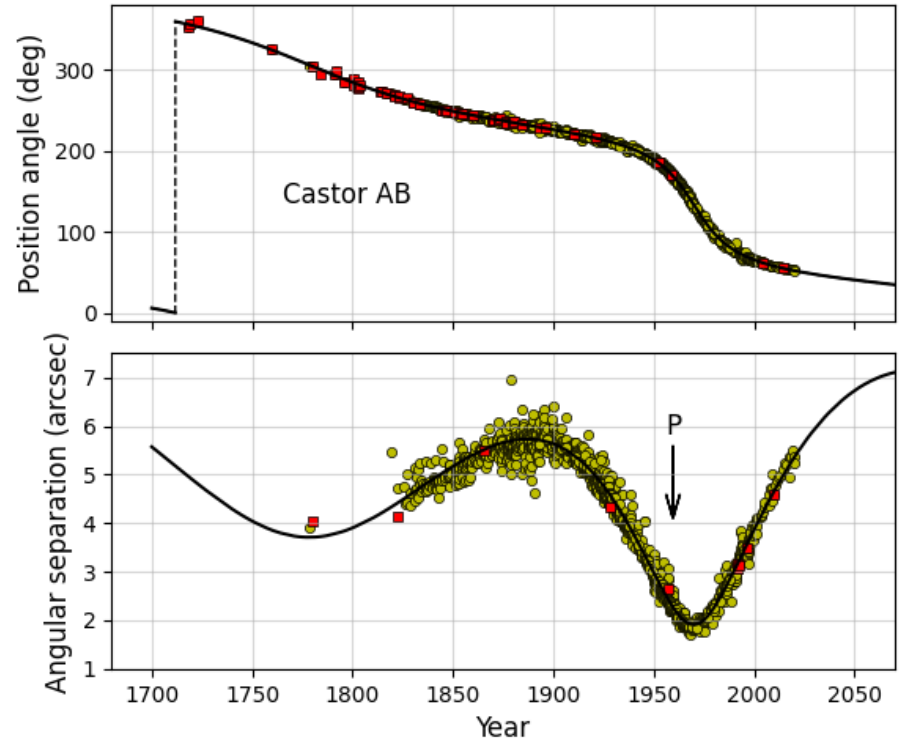
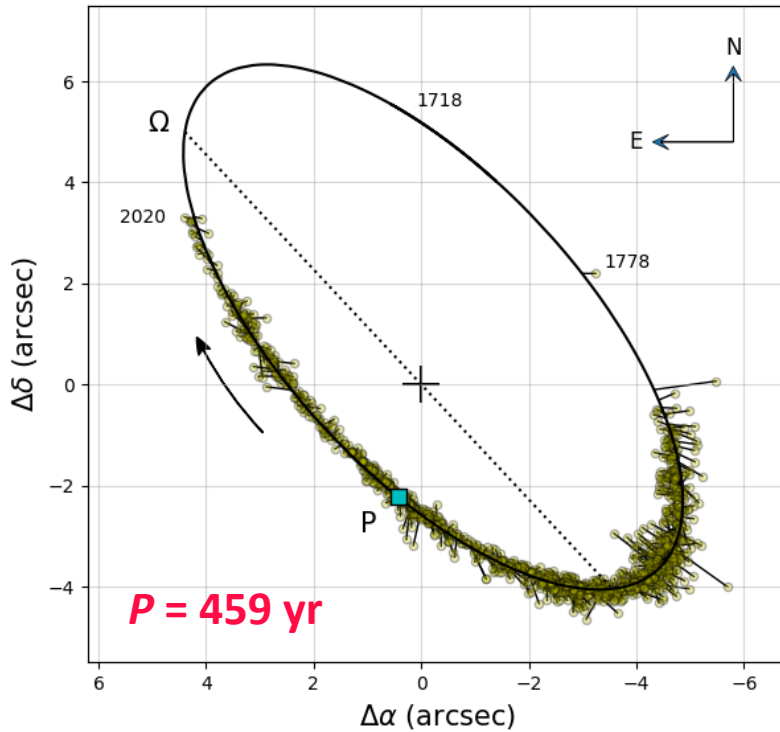


Additional Observations

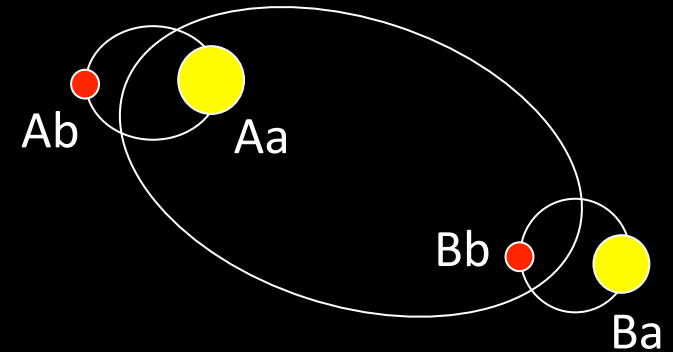
- Castor A and B have been followed spectroscopically at the CfA for nearly 30 yr, using two different instruments (DS, TRES)
 - Difference between the center-of-mass velocities of Castor A and B has changed sign compared to 100 yr ago: Constraint on the outer orbit
- Visual observers have monitored the AB pair for more than 300 yr
- Hipparcos intermediate astrometric data provide additional constraints

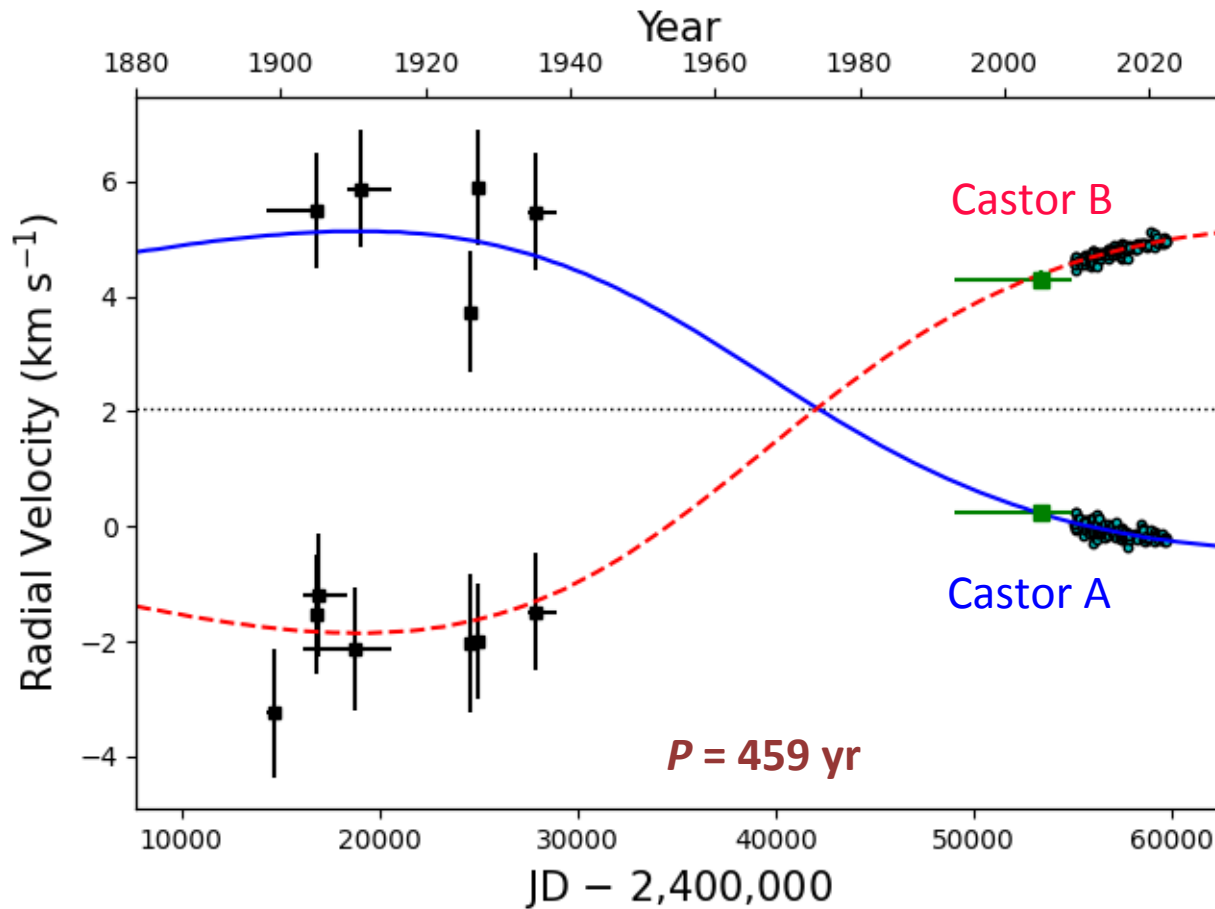


Visual Orbit of Castor AB



- Joint orbital solution (CHARA, RVs, visual observations, Hipparcos), solving for the spectroscopic and astrometric elements of all three orbits in the AB system, including the mutual inclination angles
- Aided by the Gaia parallax of Castor C





Modern and historical velocities in the outer orbit (historical RVs not used in the fit)

$$M_{Aa} = 2.371 \pm 0.015 M_{\odot}$$

$$M_{Ab} = 0.386 \pm 0.002 M_{\odot}$$

$$M_{Ba} = 1.789 \pm 0.016 M_{\odot}$$

$$M_{Bb} = 0.387 \pm 0.002 M_{\odot}$$

(All better than 1%)

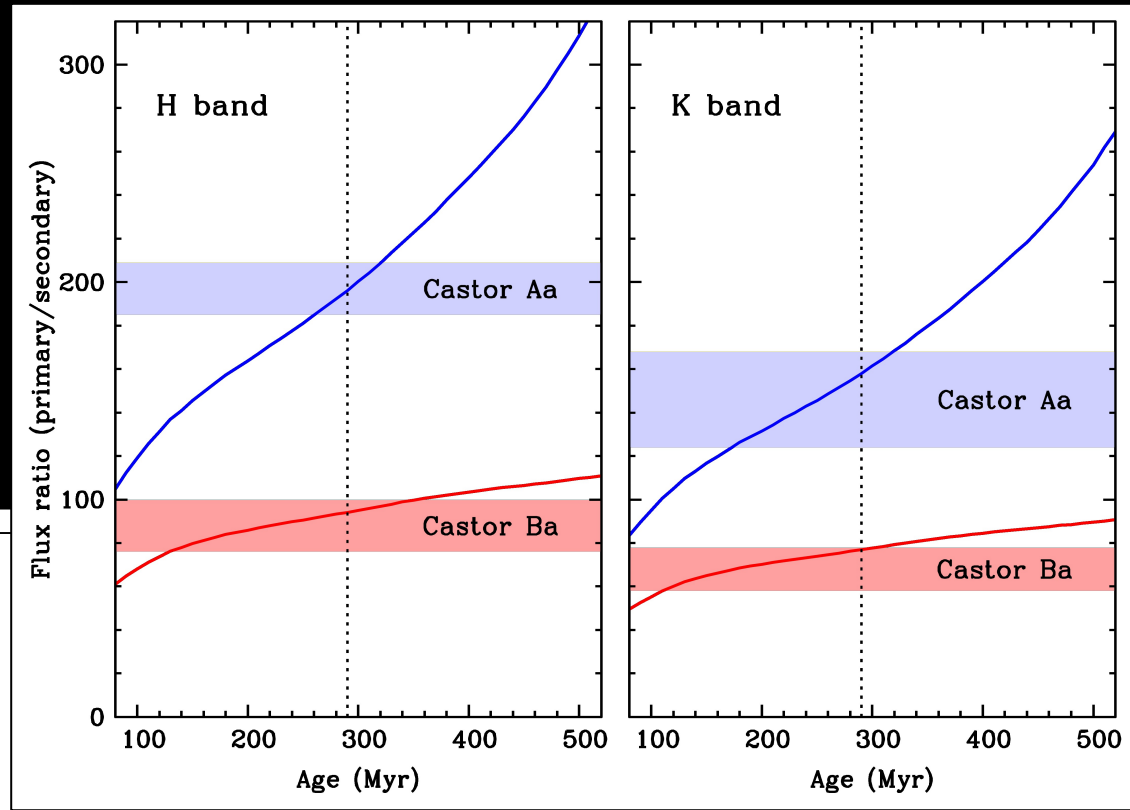
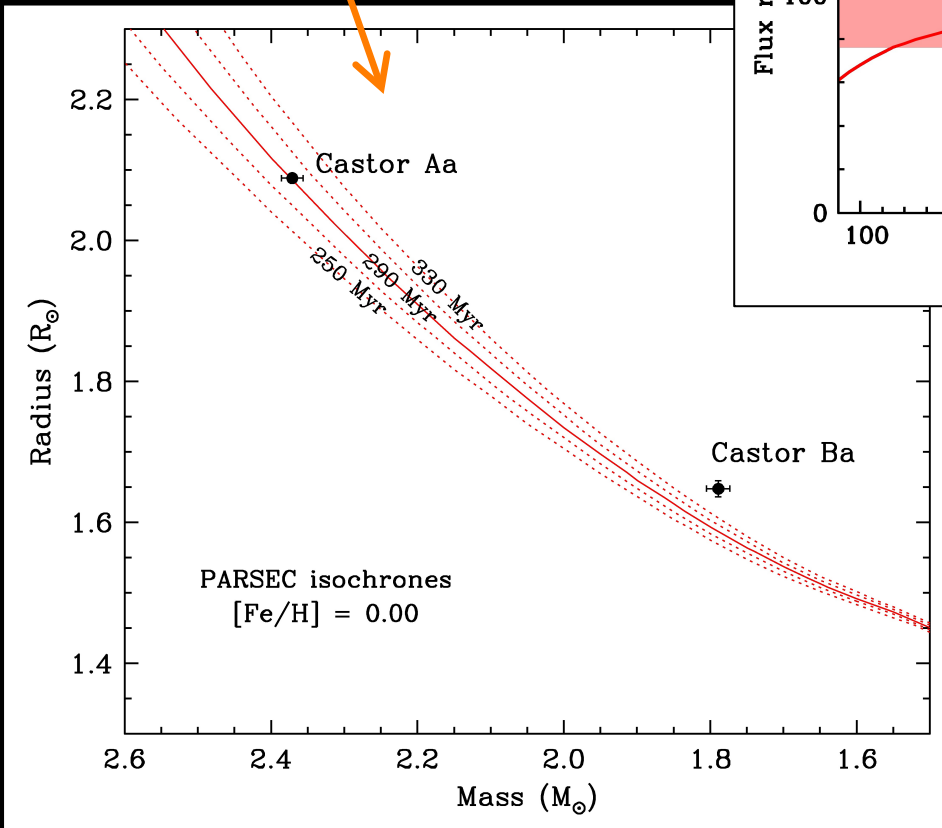
- Mutual inclination angles

- Orbit of Castor A inclined 92.34 ± 0.19 deg relative to orbit of AB → retrograde
- Orbit of Castor B inclined 59.68 ± 0.20 deg relative to orbit of AB
- Orbit of Castor A inclined 76.12 ± 0.24 deg relative to orbit of B

Angular diameters of the primaries measured with CHARA: 1.29 and 1.02 mas

$$R_{Aa} = 2.089 \pm 0.005 R_{\odot}$$

$$R_{Ba} = 1.648 \pm 0.011 R_{\odot}$$



Stellar evolution models indicate an age of about 290 Myr

Primary/secondary flux ratio measurements in *H* and *K* bands are consistent with this age

Summary

- Castor A and B spatially resolved for the first time with the CHARA array
- First dynamical mass measurements for the four stars in the AB system, along with the radii of the primaries
- Mutual inclination angles of the orbital planes of A, B, and AB measured to better than 0.5 degrees. System known to be dynamically stable
- Slow motion of Castor C measured relative to AB. Period estimated to be 14,000 yr