# Orbit Fitting of exoplanets with RV, Relative Astrometry, and Absolute Astrometry using *orbit3d*


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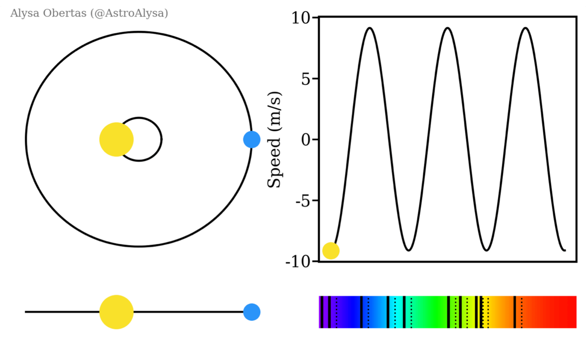



2020 Sagan Exoplanet Summer Virtual Workshop[9]
Extreme Precision Radial Velocity


## orbit3d – an orbit fitting package for the exoplanets community

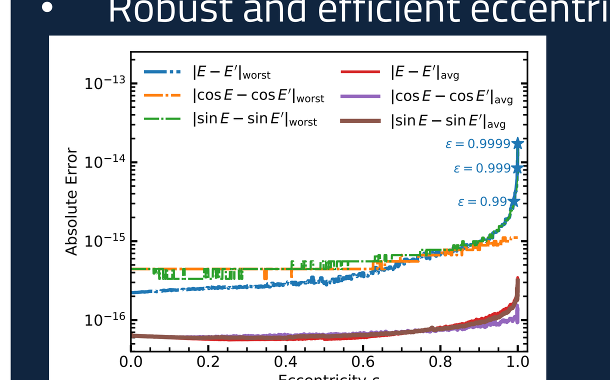
Astrometric missions like Hipparcos and GAIA measure the position of a star many times and fit an astrometric sky path. Hipparcos and GAIA measure the motion of stars in an inertial reference frame called the ICRS, defined by distant quasars. The difference in their separate measurements of proper motions (Hipparcos' around 1991 and GAIA's around 2015) indicate accelerations in an inertial frame, which may be used to constrain the orbital parameters of orbiting companions in stellar or planetary systems. Therefore, we use the cross-calibrated Hipparcos-Gaia Catalog of Accelerations (HGCA) [3] which accounts for systematics as a function of position on the sky. We employ the Hundred Thousand Orbit Fitter (HTOF) package [4] to compute synthetic Hipparcos and GAIA catalog positions and proper motions. Our Python package *orbit3d* fits orbits to a combination of the HGCA, and Radial Velocities (RVs) and/or relative astrometry. Our approach provides constrains on planetary or stellar companions without any assumptions about the primary star, though a prior on the primary mass could be imposed. Below, we demonstrate *orbit3d*'s full capabilities with a case study application to the white dwarf companion HD 159062B. We discuss the prospects of using HGCA to follow up RV or directly imaged planets.

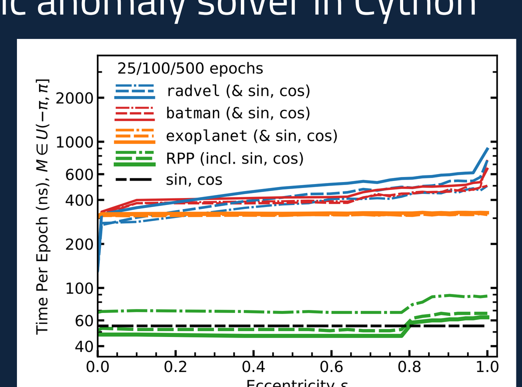
## I. MCMC orbit fitting with orbit3d

Radial velocity[6] Direct Imaging[7] GAIA DR2[8]

Advantages of *orbit3d*:

- Faster to converge
- Fit the Absolute Astrometry from Gaia and Hipparcos using the cross-calibrated HGCA
- Break degeneracy between inclination and mass
- Plot results on the go
- Robust and efficient eccentric anomaly solver in Cython




The likelihood function [1]:

$$-2\ ln\mathcal{L} = \chi^2 = \chi^2_{RV} + \chi^2_{rel\ ast} + \chi^2_{abs\ ast}$$

$$\chi^2_{RV} = \sum_{j=1}^{N_{inst}} \sum_{k=1}^{N_{RV}} \frac{\left(RV_{rel,k}+ZP_j-RV[t_k]\right)^2}{\sigma^2[RV_k]+\sigma^2_{jit}} \qquad \chi^2_{\bar\omega} = \frac{(\bar\omega - \bar\omega_{DR2})^2}{\sigma^2_{\bar\omega}[DR2]}$$

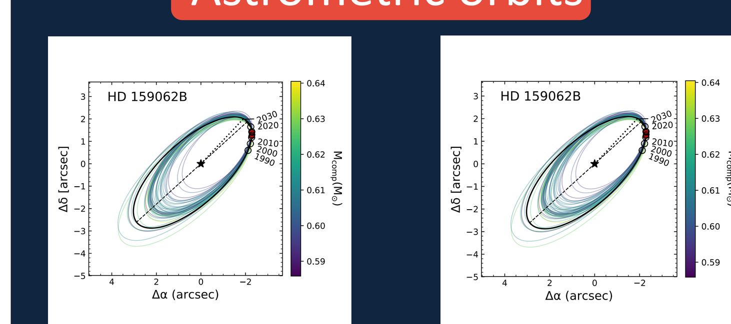
$$\chi^2_{rel\ ast} = \sum_{k=1}^{N_{inst}} \frac{\left[\theta_k-\theta[t_k]\right]^2}{\left(1-c^2_{\rho\theta,k}\right)\sigma^2[\theta_k]} + \sum_{k=1}^{N_{inst}} \frac{(\rho_k-\bar\omega\rho[t_k])}{\left(1-c^2_{\rho\theta,k}\right)\sigma^2[\rho_k]}$$

$$-2\sum_{k=1}^{N_{inst}} \frac{c_{\rho\theta,k}[\theta_k-\theta[t_k]](\rho_k-\bar\omega\rho[t_k])}{\left(1-c^2_{\rho\theta,k}\right)\sigma[\theta_k]\sigma[\rho_k]}$$

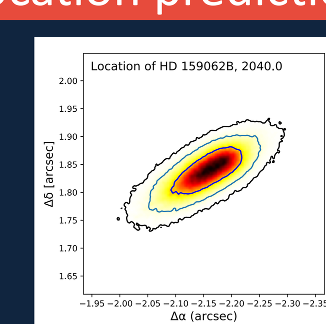
$$\chi^2_{HG} = \left(\mu_{H,o} - \bar\mu - \bar\omega\mu_H\right)^T C_H^{-1}\left(\mu_{H,o} - \bar\mu - \bar\omega\mu_H\right)$$
$$+\left(\mu_{HG,o} - \bar\mu - \bar\omega\mu_{HG}\right)^T C_{HG}^{-1}\left(\mu_{HG,o} - \bar\mu - \bar\omega\mu_{HG}\right)$$
$$+\left(\mu_{G,o} - \bar\mu - \bar\omega\mu_G\right)^T C_G^{-1}\left(\mu_{G,o} - \bar\mu - \bar\omega\mu_G\right)$$
$$\Delta\chi^2_{HG} = \left(\mu_{G,o,B} - \bar\mu - \bar\omega\mu_{G,B}\right)^T C_{G,B}^{-1}\left(\mu_{G,o,B} - \bar\mu - \bar\omega\mu_{G,B}\right)$$

## II. orbit3d Plotting example: HD 159062B

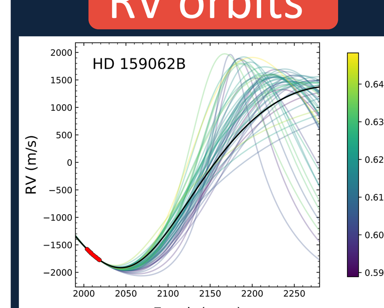
Astrometric orbits



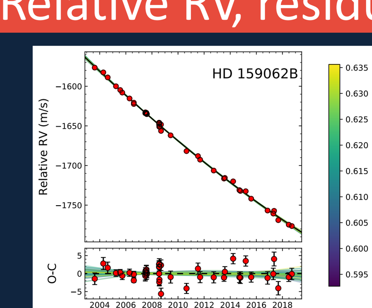
location prediction



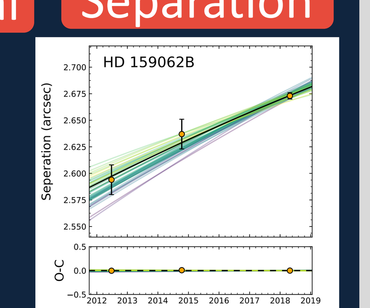
RV orbits



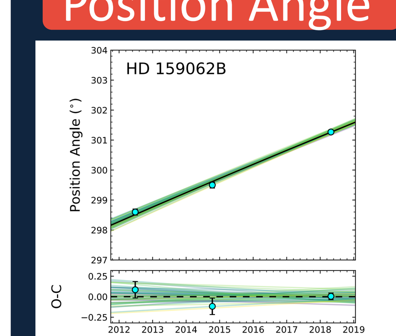
Relative RV, residual



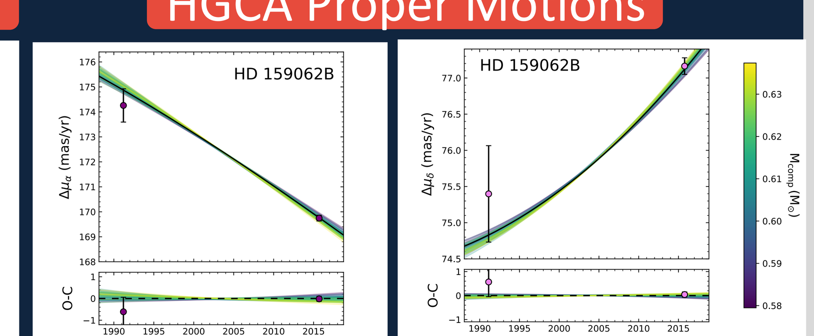
Separation



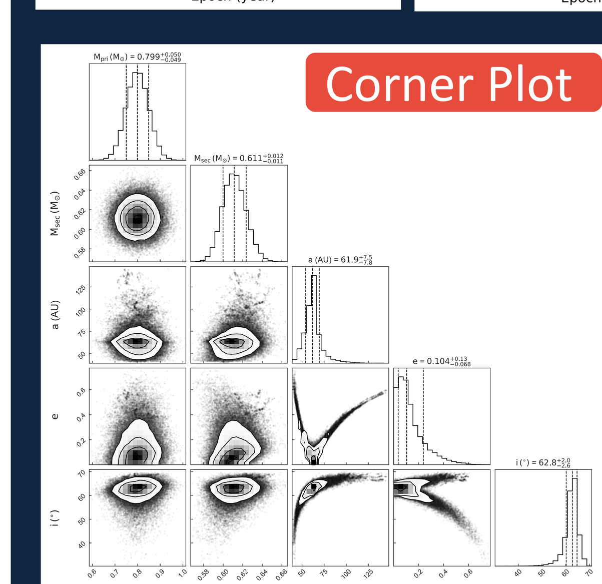
Position Angle



HGCA Proper Motions



Corner Plot



Posterior parameters

| Parameter | Median±1σ |
|---|---|
| Fitted parameters | |
| RV Jitter $\sigma$ ($\mathrm{m\,s^{-1}}$) | $0.20^{+0.19}_{-0.24}$ |
| Primary Mass ($M_\odot$) | $0.799^{+0.050}_{-0.049}$ |
| Secondary Mass ($M_\odot$) | $0.611^{+0.012}_{-0.011}$ |
| Semimajor axis a (AU) | $61.9^{+7.5}_{-7.8}$ |
| $\sqrt{e}\sin\omega$ | $-0.16^{+0.16}_{-0.11}$ |
| $\sqrt{e}\cos\omega$ | $0.01^{+0.33}_{-0.34}$ |
| Inclination | $62.8^{+2.0}_{-2.5}$ |
| Mean longitude $\lambda_{ref}$ (°) | $151.2^{+8.4}_{-7.0}$ |
| Ascending node $\Omega$ (°) | $313.5^{+1.9}_{-1.4}$ |
| Parallax (mas) | $46.118^{+0.010}_{-0.010}$ |
| Derived parameters | |
| Period | $411^{+77}_{-75}$ |
| Argument of periastron $\omega$ (°) | $4.5^{+1.3}_{-1.4}$ |
| Eccentricity e | $0.104^{+0.13}_{-0.068}$ |
| Semimajor axis (mas) | $0.300^{+0.037}_{-0.037}$ |
| Time of periastron $T_0 = t_{ref} - P\frac{\lambda-\omega}{360°}$ (JD) | $2455240^{+118}_{-365}$ |
| Mass ratio | $0.766^{+0.053}_{-0.047}$ |

## RV + Absolute Astrometry Fitting

A carefully vetted sample of the most promising targets from high-resolution imaging for HGCA follow-ups was selected by the following criteria

- Stars with one known RV planet
- Targets within Gaia distance of 50 pc
- Stars that has $\chi^2 > 11.8$ in the HGCA
- Stars that are not identified as a binary in the Exoplanet archive or in WCS

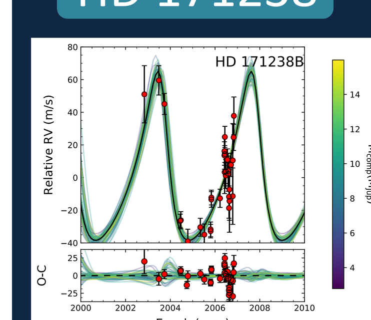
HD 87883B – A super Jupiter around a K0V MS star
Ginski Lucky Imaging with 2.2m
HD 106252B –A gas giant exoplanet orbits a G-type star
Metchev Palomar AO Imaging
HD 171238B – A gas giant planet orbiting a G8V MS star
HD 29021B – Massive planet around a G dwarf star
The SOPHIE search for northen exoplanets
HD 81040 – A gas giant exoplanet orbiting a G dwarf star

In addition, we perform orbit analysis on 3 targets from the CORALIE survey HD 98649, HD106515 and HD196067. These are massive and long period planets whose $\chi^2 > 11$ in HGCA and would thus benefit from absolute astrometry.

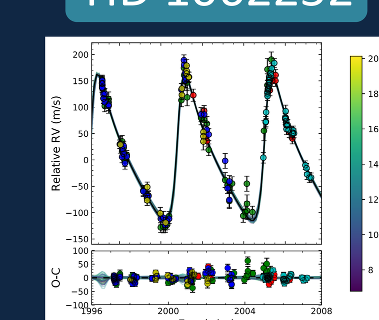
Summary of Hipparcos and Gaia Astrometry

| Star | Data Source | $\Delta\mu_\alpha$ | $\sigma[\mu_\alpha]$ | $\Delta\mu_\delta$ | $\sigma[\mu_\delta]$ | Correlation Coefficient | Epoch, $\alpha$ year | Epoch, $\delta$ year |
|---|---|---|---|---|---|---|---|---|
| HD 87883 | Hip | -64.143 | 0.665 | -60.729 | 0.466 | -0.006 | 1991.50 | 1991.09 |
| | Gaia | -64.565 | 0.098 | -61.581 | 0.119 | -0.503 | 2015.69 | 2015.84 |
| HD 106252 | Hip | 23.629 | 0.886 | -279.791 | 0.444 | -0.068 | 1991.28 | 1991.42 |
| | Gaia | 22.863 | 0.132 | -280.009 | 0.076 | -0.452 | 2015.51 | 2015.32 |
| HD 171238 | Hip | -30.543 | 1.549 | -110.295 | 1.042 | 0.069 | 1991.04 | 1991.22 |
| | Gaia | -29.578 | 0.163 | -109.110 | 0.132 | -0.142 | 2015.75 | 2015.79 |
| HD 29021 | Hip | 61.070 | 0.674 | 22.896 | 0.717 | 0.160 | 1991.11 | 1990.92 |
| | Gaia | 62.433 | 0.102 | 23.014 | 0.112 | -0.062 | 2015.84 | 2015.66 |
| HD 81040 | Hip | -151.079 | 0.836 | 35.608 | 0.525 | -0.320 | 1991.66 | 1991.34 |
| | Gaia | -151.258 | 0.138 | 36.125 | 0.097 | -0.544 | 2015.70 | 2015.85 |
| HD 98649 | Hip | -199.613 | 0.663 | -177.827 | 0.575 | -0.432 | 1991.18 | 1991.51 |
| | Gaia | -199.885 | 0.122 | -177.918 | 0.083 | 0.093 | 2015.40 | 2015.46 |
| HD 106515 | Hip | -249.217 | 1.074 | -53.572 | 0.875 | -0.372 | 1991.39 | 1991.10 |
| | Gaia | -251.577 | 0.173 | -51.389 | 0.119 | -0.310 | 2015.60 | 2015.70 |
| HD 196067 | Hip | 150.429 | 2.186 | -159.609 | 2.343 | -0.477 | 1991.31 | 1991.16 |
| | Gaia | 156.596 | 0.070 | -162.079 | 0.081 | -0.252 | 2015.61 | 2015.65 |

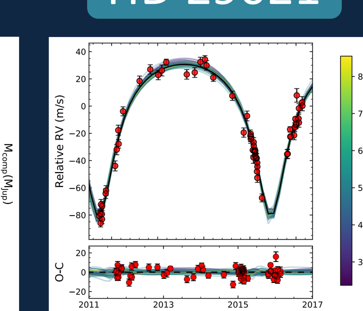
HD 171238



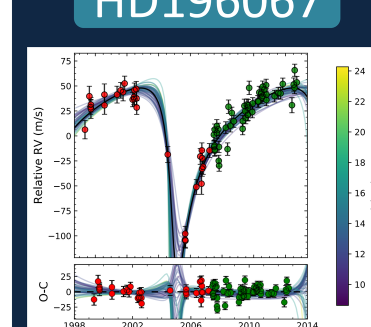
HD 1062252



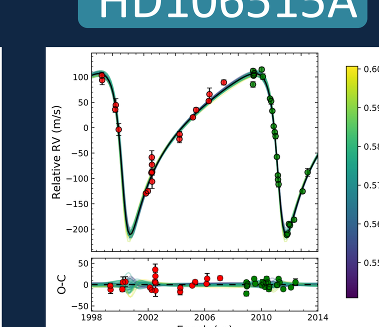
HD 29021



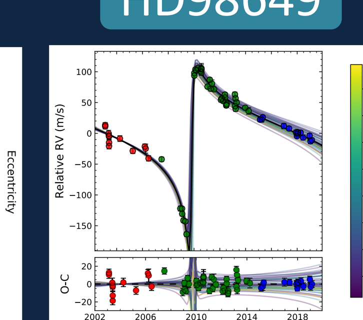
HD196067



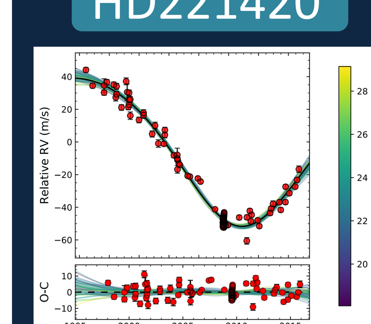
HD106515A



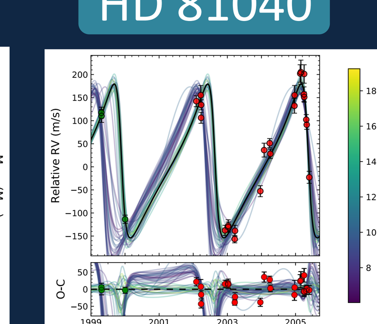
HD98649



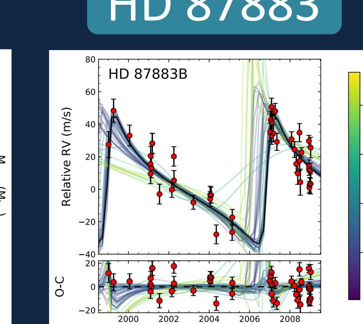
HD221420



HD 81040

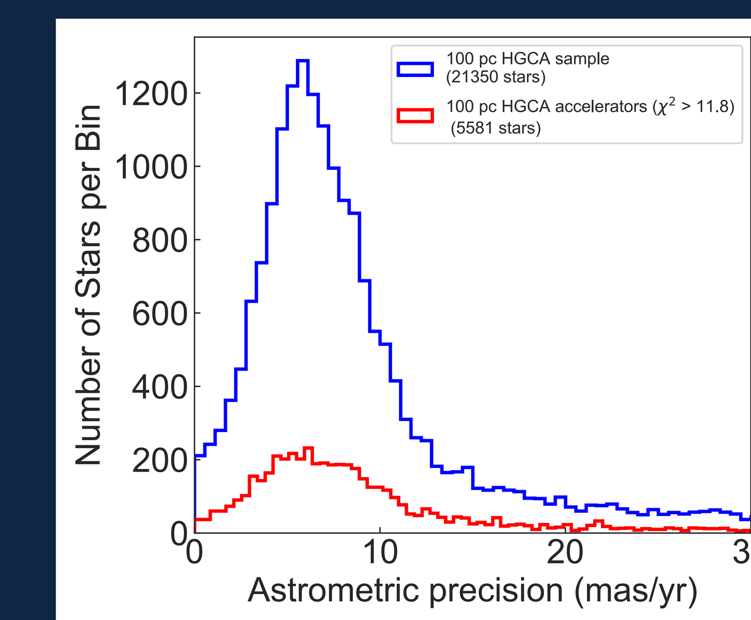


HD 87883



## Future work/ Discussion

HGCA catalog can be used to find new substellar companions reaching the planetary regime, or to follow up known RV/directly imaged companions with Absolute Astrometry.




## Conclusion

- *orbit3d* package is ready for deployment and will be available on GitHub. Described more in detail in T. Brandt , T. Dupuy, Y Li 2020 et al. In prep. [1]
- More science with orbit3d are described in Y Li, T. Brandt et al, 2020. In prep. [2]
- HD 159062B: A WD/MS system discovered by Hirsh et al. [4]. Our use of HGCA astrometry improved our constraint of HD 159062B's mass by an order of magnitude. Furthermore, in Figure 6 of [4], we are firmly placing the system on the long period and low eccentricity end. Therefore, short period and high eccentricity are strongly disfavored by our new results. This would seem to disfavor an interacting binary scenario such as the Ba or CH theory discussed above, so we should not expect barium enrichment.
- HD 81040B: Planning follow-up of RVs to further constrain its orbit with LCO.
- HD 221420B: Direct imaging follow-up with SPHERE.

## References


[1] T. Brandt , T. Dupuy, Y Li et al, 2020. In prep.
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