LOFTI: Orbit Fitting of Wide Stellar Binaries with Gaia

The LOFTI-Gaia package will fit orbital elements to the astrometry provided by Gaia DR2 only.

Written by Logan A. Pearce, 2019
If you use LOFTI in your work please cite Pearce et al. 2019

Fitting orbital parameters:

Begin by importing the "fitorbit" module

In [1]:
```
from lofti_gaia.lofti import fitorbit
```

Let's look at the arguements and what it writes out

In [2]:
```
help(fitorbit)
```

```
Help on function fitorbit in module lofti_gaia.lofti:

fitorbit(source_id1, source_id2, mass1=0, mass2=0, d=2015.5, verbose=Fa
lse, output_directory='.', rank=0, accept_min=10000)
    Fit orbital parameters to binary stars using only the RA/DEC positi
ons and proper motions from
    Gaia DR2 by inputting the source ids of the two objects and their m
asses only.
    Writes accepted orbital parameters to a file.

    Parameters:
    -----------
    source_id1, source_id2 : int
        Gaia DR2 source identifiers, found in the Gaia archive or Simba
d.  Fit will be
        of source_id2 relative to source_id1.
    mass1, mass2 : tuple, flt [Msol]
        masses of primary and secondary objects, entered as a tuple wit
h the error.  For example:
        mass1 = (1.0,0.2) is a 1 solar mass star with error of \pm 0.2
solar masses.  If mass1 or mass2 = 0,
        script will prompt user to input a tuple mass.  Default = 0.
    d : flt [decimalyear]
        observation date.  Default = 2015.5, the DR2 obs date.
    verbose : bool
        if set to True, script will print constraints to screen, ask fo
r confrimation before proceeding,
        and print regular updates on number of accepted orbits.  If set
to False, script will print a progress bar
        to screen.  Default = False.
    output_name : str
        directory to write output files to.  If verbose = True, script
will prompt for directory, if
        verbose = False it will write files to current directly unless
the name argument is specified.
    rank : int
        if running in parallel processing mode, set this keyword to the
rank of each process.  Else it is NA.
    accept_min : int
        when the number of accepted orbits reaches this number, script
will terminate

    Returns:
    --------
    output files :
        writes out accepted orbits to a file called name+rank+'_accepte
d'.  The columns of the file are:
            semi-major axis [arcsec]
            period [yrs]
            epoch of periastron passage [decimalyear]
            eccentricity
            inclination [deg]
            argument of periastron [deg]
            position angle of nodes [deg]
            chi-squared value of the orbit
            probability of orbit generating observations
            random uniform number to determine acceptance
```

```
        writes out a human-readable text file of the constraints it com
puted from Gaia data, called "constraints.txt".
            deltaRA [mas]: relative RA separation
            deltaDec [mas]: relative DEC separation
            pmRA_kms [km/s]: relative proper motion in RA
            pmDec_kms [km/s]: relative proper motion in DEC
            deltarv [km/s]: relative radial velocity (if applicable)
            total_pos_velocity [mas/yr]: total velocity vector in the p
lane of the sky
            total_velocity_kms [km.s]: total velocity vector in the pla
ne of the sky
            rho [mas]: separation
            pa [deg]: position angle
            delta_mag [mag]: contrast in magnitudes
            d_star [pc]: distance
        writes out the above parameters to a machine readable file call
ed "constraints.pkl"

    Notes:
    ------
    Future versions will adapt to new Gaia data releases and additional
constraints.  See
    Pearce et al. 2019 for more information, including a discussion of
how to determine if
    the Gaia DR2 solution is of adequate quality to provide meaningful
and accurate constraints
    for orbit fitting.
    If you use this package, please cite Pearce et al. 2019.

    Written by Logan A. Pearce, 2019
```

Example: DS Tuc AB:

The first use of this technique was for DS Tuc AB, and published in Newton et al. 2019. Both components have well-defined solutions in Gaia DR2, including radial velocities. It makes a good demostration case.
Let's start by making a new directory to hold the output file

In [3]:
```
import os
os.system('mkdir DSTucAB')
```

Out[3]: 256

All we need to give the fitter is the Gaia source ID numbers for the two components:

In [4]:
```
DSTucA = 6387058411482257536
DSTucB = 6387058411482257280
```

and their masses (masses are from Newton et al. 2019). fitorbit looks for the mass and its error to be entered as a tuple:

In [5]:
```
massA = (0.97,0.04)
massB = (0.87, 0.04)
```

Run the fitter by calling fitorbit. Let's tell it to output files to the directory we made, set a low minimum accepted orbit number for demonstration purposes, and set verbose to True. When verbose is set to True, the fitter pauses and asks you to check that the constraints it will use look reasonable and like you expect them to, and makes sure it will write out the file where you are expecting to find it. It will also print an update when it finds lower chi-squared values, and periodically prints the number of orbits it's found.

To get a good posterior sample, you should look for thousands of accepted orbits. I typically aim for 100,000 orbits as a good sample. For demonstration purposes, let's just ask for 50 orbits.

In [6]:
```
fitorbit(DSTucA, DSTucB,
          mass1 = massA,
          mass2 = massB,
          output_directory = "DSTucAB",
          verbose = True,
          accept_min = 50
         )
```

```
Computing constraints.
Created TAP+ (v1.0.1) - Connection:
        Host: gea.esac.esa.int
        Use HTTPS: False
        Port: 80
        SSL Port: 443
Finished computing constraints:
Delta RA, err in mas: -1146.6530524844409 0.015946495992160997
Delta Dec, err in mas: 5240.634364261226 0.03140411699483365

pmRA, err in km/s: -0.30173712008430653 0.020545393993457103
pmDec, err in km/s: 0.3543703626789322 0.012283970508770524
deltaRV, err im km/s (pos towards observer): 1.8793611665844168 0.73547
12000512816

Total relative velocity [km/s]: 1.9361358521672773 +/- 1.87951360825383
42
Total plane-of-sky relative velocity [mas/yr]: 2.2246301214145014 +/-
0.11376315413334326

sep,err [mas] 5364.6119862415935 0.030969548907948157 pa,err [deg]: 34
7.6581552726796 0.00017916102851933162
sep [AU] 236.76199216882884
sep, err [km] (35419089891.146866, 0.0) (204472.0549169436, 0.0)
D_star 44.1340385429632 +\- 0.06336868730526682
Delta Gmag -1.0800505

Does this look good? Hit enter to start the fit, n to exit
Yeehaw let's go
Chi-min: 3.511843864585613
Ok, starting loop
I will write files out to this directory: DSTucAB
Is that right? Hit enter to proceed, n for no:
I will be looking for  50  orbits.
Ok? Hit enter to proceed, n for no:
Loop count rank  0 :  0
Rank  0  has found  0 accepted orbits
Found new chi min:  2.9617637426420282
Found new chi min:  1.3122232843490662
Found new chi min:  1.1215605441353447
Found new chi min:  0.44002769230980393
Loop count rank  0 :  10
Rank  0  has found  10 accepted orbits
Loop count rank  0 :  20
Rank  0  has found  17 accepted orbits
Loop count rank  0 :  30
Rank  0  has found  20 accepted orbits
Found new chi min:  0.204909661487927
Loop count rank  0 :  40
Rank  0  has found  23 accepted orbits
Loop count rank  0 :  50
Rank  0  has found  26 accepted orbits
Loop count rank  0 :  60
Rank  0  has found  34 accepted orbits
Loop count rank  0 :  70
Rank  0  has found  45 accepted orbits
Loop count rank  0 :  80
```

```
Rank  0  has found  46 accepted orbits
Loop count rank  0 :  90
Rank  0  has found  54 accepted orbits

Found  54  orbits, finishing up...
This operation took 53.195857763290405 seconds
and 0.014776627156469557 hours
```

With verbose = False (default), the print statements are supressed, the script does not pause to check with the user before proceeding, and a progress bar reports the status of the fit.

In [7]:
```
from lofti_gaia.lofti import fitorbit

DSTucA = 6387058411482257536
DSTucB = 6387058411482257280
massA = (0.97,0.04)
massB = (0.87, 0.04)

fitorbit(DSTucA, DSTucB,
         mass1 = massA,
         mass2 = massB,
         output_directory = "DSTucAB",
         accept_min = 100
        )
```

```
Computing constraints.
Ok, starting loop
100% (107 of 100): |####################|  Done...

Found  107  orbits, finishing up...
This operation took 23.963433027267456 seconds
and 0.00665650917424096 hours
```

If you forget to enter the masses, the script will prompt you to enter the mass and error with a space between them.

In [8]:
```
fitorbit(DSTucA, DSTucB,
         output_directory = "DSTucAB",
         accept_min = 100
        )
```

```
Computing constraints.
Enter mass of object 1 and error separated by a space (ex: 1.02 0.2):0.
97 0.04
Enter mass of object 2 and error separated by a space (ex: 1.02 0.2):0.
87 0.04
Ok, starting loop
100% (105 of 100): |####################|  Done...

Found  105  orbits, finishing up...
This operation took 17.085912704467773 seconds
and 0.004746086862352159 hours
```

Plotting the output

lofti_gaia offers and optional setting of plotting tools to inspect the results of fitorbit, called lofti_gaia.lofti.makeplots.

In [9]:
```
from lofti_gaia.lofti import makeplots
help(makeplots)
```

```
Help on function makeplots in module lofti_gaia.lofti:

makeplots(input_directory, rank=0, Collect_into_one_file=False, limit=
0.0, roll_w=False, plot_posteriors=True, plot_orbit_plane=True, plot_3d
=True, axlim=6)
    Produce plots and summary statistics for the output from lofti.fito
rbit.

    Parameters:
    -----------
    input_directory : str
        Gaia DR2 source identifiers, found in the Gaia archive or Simba
d.  Fit will be
        of source_id2 relative to source_id1.
    rank : int
        Set this parameter to iterate through processes if running on m
ultiple threads
    Collect_into_one_file : bool
        Set to true if running on multiple process and the script did n
ot terminate on its own.  This will
        tell the script to collect output from each multiple process an
d put into one file.
    limit : int [au]
        Sometimes semi-major axis posteriors will have very long tails.
If you wish to truncate the sma histogram
        at some value for clarity, set the limit parameter to that valu
e.
    roll_w : bool
        I you wish to have arg of periastron wrap around zero, set this
to True
    plot_posteriors : bool
        set to True to make posterior histogram plots of X, Y, Z, dotX,
dotY, dotZ, ddotX, ddotY, ddotZ
    plot_orbit_plane : bool
        set to True to generate plot of 100 random orbits from the post
erior in XY plane, XZ plane, and YZ plane
    plot_3d: bool
        set to True to generare a 3D plot of 20 random orbits from the
posterior.
    axlim: flt [arcsec]
        if plot_orbits = True or plot_3d = True, set this parameter to
set the axis limits (in arcsec) for the plots

    Returns:
    --------
    output files :
        stats: summary statistics for each orbital parameter + periastr
on distance, including:
            Mean    Std    Mode    68% Min Cred Int    95% Min Cred Int
        hist.pdf: 1d histogram of orbital parameter posteriors
        observable_posteriors (if plot_posteriors = True): directory co
ntaining 1d histograms of
            posteriors for X, Y, Z, dotX, dotY, dotZ, ddotX, ddotY, ddo
tZ
        orbits.png (if plot_orbits = True): plot of a selection of 100
random orbits from fitorbit posterior in
            RA/DEC, colored by orbital phase
```

```
        orbits_yz.png, orbits_xz.png (if plot_orbits = True): plots of
the same 100 orbits in YZ and XZ planes
        orbits_3d.png (if plot_3d = True): 3d plot of 20 random orbits
from posterior

    Notes:
    ------
    These are suggested summary stats and plots.  For more versatility
you can use
    the fitorbit output with your own plotting scheme.
    If you use this package, please cite Pearce et al. 2019.

    Written by Logan A. Pearce, 2019
```

The plots are written out to files in the directory you specified when you called makeplots.

In [10]:
```
directory = 'DSTucAB'
makeplots(directory,
                  rank = 0,
                  Collect_into_one_file = False,
                  limit = 0.,
                  roll_w = False,
                  plot_posteriors = True,
                  plot_orbit_plane = True,
                  plot_3d = True
               )
```

```
Writing out stats
Making histograms
Plotting observable posteriors
Plotting orbits
XY plane
XZ plane
YZ plane
3D
```

As with fitorbit, the output of this script is saved into the directory you set at the beginning. Figures are saved as pngs.

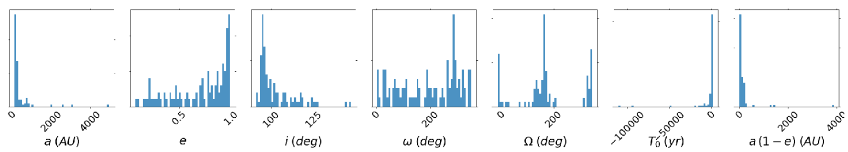
Let's look at the figures this code generated: (If you're having trouble viewing within the notebook, there are examples in the github repo)

hists.png:

Histograms won't look very nice for this tutorial because we only accepted ~100 orbits. To really sample the posteriors well, you need ~100,000 sample orbits.

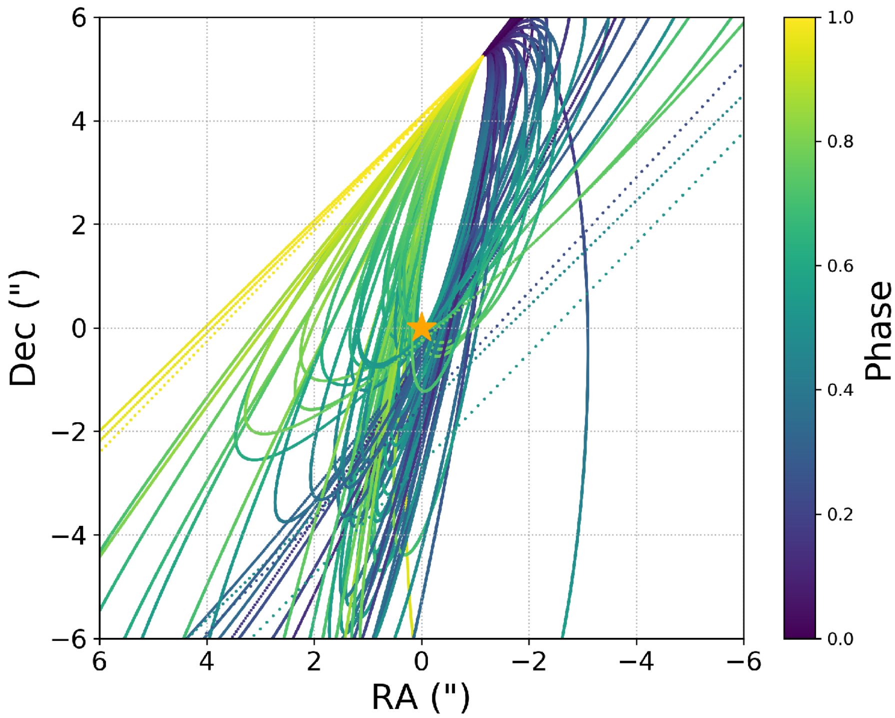
In [11]:
```
import matplotlib.image as mpimg
directory = 'DSTucAB'

%matplotlib notebook
img = mpimg.imread(directory+'/hists.png')
plt.figure(figsize=(11, 5.5/3))
plt.imshow(img)
plt.axis('off')
plt.show()
```



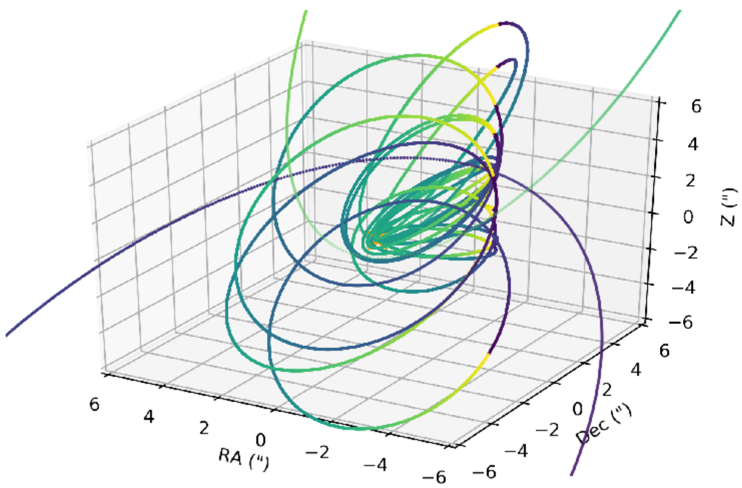
orbits.png

In [12]:
```
%matplotlib notebook
img = mpimg.imread(directory+'/orbits.png')
plt.figure(figsize=(10, 9.))
plt.imshow(img)
plt.axis('off')
plt.show()
```



orbits_3d.png

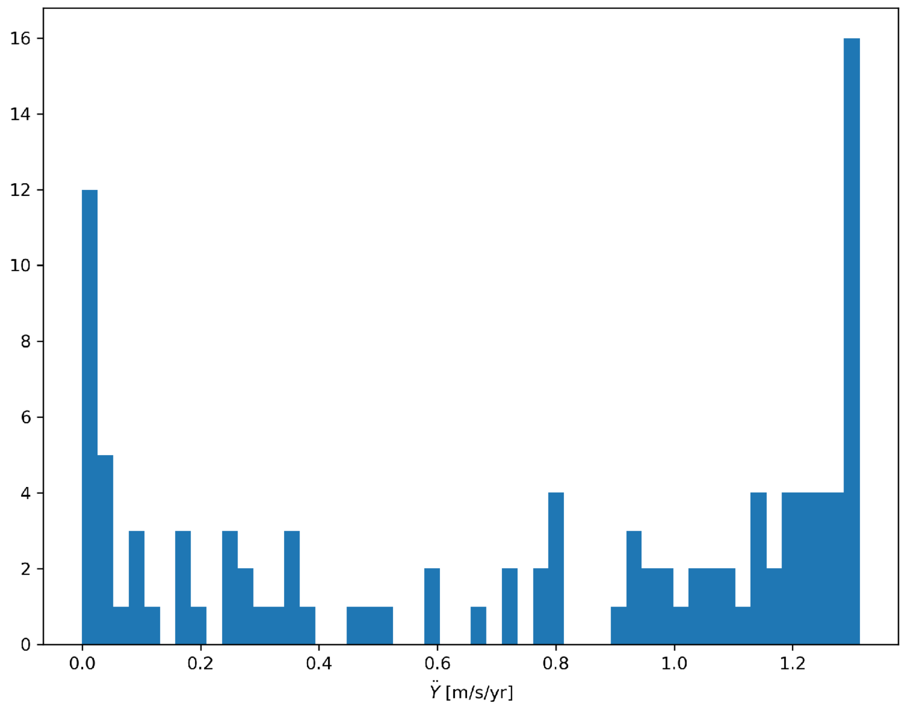
In [13]:
```
%matplotlib notebook
img = mpimg.imread(directory+'/orbits_3d.png')
plt.figure(figsize=(5, 6))
plt.imshow(img)
plt.axis('off')
plt.show()
```



One of the observables posteriors:

This is the distribution of acceleration in RA from the orbits in the posterior sample:

In [14]:
```
%matplotlib notebook
img = mpimg.imread(directory+'/observable_posteriors/yddot.png')
plt.figure(figsize=(10, 9.))
plt.imshow(img)
plt.axis('off')
plt.show()
```



stats.txt:

The stats file looks like this inside (the parameters are already written in Latex math mode):

Parameter Mean Std Mode 68% Min Cred Int 95% Min Cred Int
$a\ (AU)$ 440.273860033696 778.7828994666231 167.91369902260953 (120.78742643128001, 335.5722381365086) (120.78742643128001, 1440.6607692140242)
e 0.7363533729151298 0.25417521870515686 0.9354707541002492 (0.7079602799311652, 0.9944789694374682) (0.11403236837364339, 0.9944789694374682)
$i\ (deg)$ 102.21552571902514 12.315962182778556 96.93037897540756 (93.85757612975858, 104.21407925155971) (91.20949059969848, 129.6667081849308)
$\omega\ (deg)$ 170.14767463219783 99.64182945955947 110.92869998371395 (13.407759062840405, 220.04147746284139) (5.060697734275732, 336.04000373968086)
$\Omega\ (deg)$ 37.72898415688386 94.40123009172831 -29.405473241926238 (-45.72234936546789, 143.51214034948345) (-119.84686434942489, 179.66687380258452)
$T_0\ (yr)$ -5266.072718030055 41405.54729054067 1390.9519132615283 (-387.5345674226005, 1637.8029937252832) (-13979.8862767336, 1939.049329542796)
$a\,(1-e)\ (AU)$ 109.41920890604749 219.0675705854163 26.869332294301532 (0.9391792185192334, 117.30940253868981) (0.9391792185192334, 263.2353692706762)

GIGO: Poor Gaia solutions will give poor orbit fits!

The Gaia astrometric solution assumes that all point sources are single stars, and that their motion was linear (no acceleration) during the time series images used to arrive at the astrometric solution. If a source is actually an unresolved multiple system, or if the binary is resolved but orbital acceleration was large enough to affect the astrometric solution, the solution will not be reliable. This is best quantified in the Renormalized Unit Wight Error (RUWE) parameter (see
https://gea.esac.esa.int/archive/documentation/GDR2/Gaia_archive/chap_datamodel/sec_dm_main_tables/ssec_
(https://gea.esac.esa.int/archive/documentation/GDR2/Gaia_archive/chap_datamodel/sec_dm_main_tables/ssec_
And RUWE >~ 1.2 indicates an unreliable solution.

LOFTI will look at the RUWE and raise a warning if it's greater than 1.2, and ask if you really want to do this.

Kepler 444 is a triple system (Dupuy et al. 2016). Kepler 444 A is resolved in Gaia, but Kepler 444 B and C aren't resolved.

In [3]:
```
Kepler444BC = 2101486923382009472
Kepler444A = 2101486923385239808
fitorbit(Kepler444BC, Kepler444A, verbose=True)
```

```
Computing constraints.
Created TAP+ (v1.0.1) - Connection:
        Host: gea.esac.esa.int
        Use HTTPS: False
        Port: 80
        SSL Port: 443
Finished computing constraints:
Delta RA, err in mas: 1754.9243128632852 0.3189517009128414
Delta Dec, err in mas: 544.4546301538144 0.5744290942303749

pmRA, err in km/s: -1.4105342203867228 0.16512004559558907
pmDec, err in km/s: 1.9312076961988849 0.175587192939648
deltaRV, err im km/s (pos towards observer): 0.0 0.0

Total relative velocity [km/s]: 2.391478612227127 +/- 0.241030064062379
12
Total plane-of-sky relative velocity [mas/yr]: 15.03161860446753 +/- 1.
5086728000824803

sep,err [mas] 1837.4412911195748 0.34862183330431934 pa,err [deg]: 72.7
6381454087225 0.01736614347812121
sep [AU] 61.666994140223395
sep, err [km] (9225251015.846796, 0.0) (1750327.4457696672, 0.0)
D_star 33.561341218498995 +\- 0.28704379047656037
Delta Gmag 3.6348228
RUWE source 1: 16.686954
RUWE source 2: 1.0002892

Does this look good? Hit enter to start the fit, n to exit:
Yeehaw let's go
WARNING: RUWE for one or more of your solutions is greater than 1.2. Th
is indicates
            that the source might be an unresolved binary or experienci
ng acceleration
            during the observation.  Orbit fit results may not be trust
worthy.  Do you
            wish to continue?
            Hit enter to proceed, n to exit: n
```

The RUWE for Kepler 444 BC is much too large to give a reliable orbit fit, and the script raised a warning to let us know this. GL 896 is another case where the RUWE for one source is too large, this time because the orbit exhibited acceleration during the Gaia observations. See Pearce et al. 2019 for further discussion.

In [ ]:
```

```