LOFTI: Orbit Fitting of Wide Stellar Binaries with Gaia DR2

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_gaiaDR2.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_gaiaDR2.lofti:

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

    Parameters:
    -----------
    source_id1, source_id2 : int
        Gaia DR2 source identifiers, found in the Gaia archive or Simbad.
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 with
the error.  For example:
        mass1 = (1.0,0.2) is a 1 solar mass star with error of \pm 0.2 so
lar 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 for
confrimation before proceeding,
        and print regular updates on number of accepted orbits.  If set t
o False, script will print a progress bar
        to screen.  Default = False.
    output_directory : str
        directory to write output files to.  If verbose = True, script wi
ll prompt for directory, if
        verbose = False it will write files to current directly unless th
e name argument is specified.
    rank : int
        if running in parallel processing mode, set this keyword to the r
ank of each process.  Else it is NA.
    accept_min : int
        when the number of accepted orbits reaches this number, script wi
ll 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 compu
ted 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 pla
ne of the sky
            total_velocity_kms [km.s]: total velocity vector in the plane
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 called
"constraints.pkl"

    Notes:
    ------
    Future versions will adapt to new Gaia data releases and additional c
onstraints.  See
    Pearce et al. 2019 for more information, including a discussion of ho
w to determine if
    the Gaia DR2 solution is of adequate quality to provide meaningful an
d 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]:
```python
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]:
```python
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
        )
```

```
pmRA, err in km/s: -0.30173712008430653 0.020142640541549427
pmDec, err in km/s: 0.3543703626789322 0.012019642763754569
deltaRV, err im km/s (pos towards observer): 1.8793611665844168 0.7210784
568095868

Total relative velocity [km/s]: 1.9361358521672773 +/- 0.7214598662815899
Total plane-of-sky relative velocity [mas/yr]: 2.2246301214145014 +/- 0.1
1376315413334326

sep,err [mas] 5364.61182495538 0.030652493687488146 pa,err [deg]: 347.658
1545714772 0.00018191461322 53892
sep [AU] 236.7619850506169
sep, err [km] (35419088826.27751, 0.0) (202378.74278500729, 0.0)
D_star 44.1340385429632 +\- 0.06336868730526682
Delta Gmag -1.0800505
RUWE source 1: 1.0344639

RUWE source 2: 1.0149378

Does this look good? Hit enter to start the fit, n to exit:
```

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_gaiaDR2.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% (138 of 100): |####################|  Done...

Found  138  orbits, finishing up...
This operation took 22.600182056427002 seconds
and 0.006277828349007501 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% (110 of 100): |####################|  Done...

Found  110  orbits, finishing up...
This operation took 17.39067792892456 seconds
and 0.004830743869145711 hours
```

Show constraints:

If you want to examine the Gaia DR2 astrometric solutions without performing a fit, use showconstraints():

In [9]:
```
from lofti_gaiaDR2.lofti import showconstraints
showconstraints(DSTucA, DSTucB)
```

```
Finished computing constraints:
Delta RA, err in mas: -1146.653198388634 0.01607406211460945
Delta Dec, err in mas: 5240.63449891825 0.03188410660735349

pmRA, err in km/s: -0.30173712008430653 0.02009352968906262
pmDec, err in km/s: 0.3543703626789322 0.012219615349114104
deltaRV, err im km/s (pos towards observer): 1.8793611665844168 0.7241230
42529392

Total relative velocity [km/s]: 1.9361358521672773 +/- 0.7245048306648266
Total plane-of-sky relative velocity [mas/yr]: 2.2246301214145014 +/- 0.1
1376315413334326

sep,err [mas] 5364.61214897371 0.03134508575616734 pa,err [deg]: 347.6581
540577603 0.00018264827207337692
sep [AU] 236.76199935085432
sep, err [km] (35419090965.562584, 0.0) (206951.4837029632, 0.0)
D_star 44.1340385429632 +\- 0.06336868730526682
Delta Gmag -1.0800505
RUWE source 1: 1.0344639
RUWE source 2: 1.0149378
```

Plotting the output

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

In [10]:
```
from lofti_gaiaDR2.lofti import makeplots
help(makeplots)
```

```
Help on function makeplots in module lofti_gaiaDR2.lofti:

makeplots(input_directory, rank=0, Collect_into_one_file=False, limit=0.
0, roll_w=False, limit_w=False, limit_O=False, plot_posteriors=True, plot
_orbit_plane=True, plot_3d=True, axlim=6, log_a=True, plot_style='defaul
t', saveas='png')
    Produce plots and summary statistics for the output from lofti.fitorb
it.

    Parameters:
    -----------
    input_directory : str
        Gaia DR2 source identifiers, found in the Gaia archive or Simbad.
Fit will be
        of source_id2 relative to source_id1.
    rank : int
        Set this parameter to iterate through processes if running on mul
tiple threads
    Collect_into_one_file : bool
        Set to true if running on multiple process and the script did not
terminate on its own.  This will
        tell the script to collect output from each multiple process and
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 value.
    roll_w : bool
        If you wish to have arg of periastron wrap around zero, set this
to True
    limit_w : bool
        If you wish to limit arg of peri to the interval [0,180], set thi
s to True
        (recommended in the absence of RV information).  Default = False
    limit_O : bool
        If you wish to limit position angle of nodes to the interval [0,1
80], set this to True
        (Do not limit both w and O, recommend limiting w instead of O).
Default = False
    plot_posteriors : bool
        set to True to make posterior histogram plots of X, Y, Z, dotX, d
otY, dotZ, ddotX, ddotY, ddotZ
    plot_orbit_plane : bool
        set to True to generate plot of 100 random orbits from the poster
ior 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 po
sterior.
    axlim : flt [arcsec]
        if plot_orbits = True or plot_3d = True, set this parameter to se
t the axis limits (in arcsec) for the plots
    log_a : bool
        set to True to plot semi-major axis and periastron in log scale i
n marginalized posterior
```

```
    plot_style : str
        matplotlib plotting style.  Default = True
    saveas : str
        keyword for plt.savefig to set the output format.

    Returns:
    --------
    output files :
        stats: summary statistics for each orbital parameter + periastron
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 cont
aining 1d histograms of
            posteriors for X, Y, Z, dotX, dotY, dotZ, ddotX, ddotY, ddotZ
        orbits.png (if plot_orbits = True): plot of a selection of 100 ra
ndom orbits from fitorbit posterior in
            RA/DEC, colored by orbital phase
        orbits_yz.png, orbits_xz.png (if plot_orbits = True): plots of th
e same 100 orbits in YZ and XZ planes
        orbits_3d.png (if plot_3d = True): 3d plot of 20 random orbits fr
om posterior

    Notes:
    ------
    These are suggested summary stats and plots.  For more versatility yo
u 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 [3]:

```python
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)

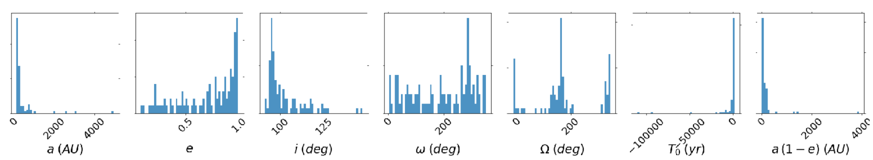
hists.png:

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()
```

<IPython.core.display.Javascript object>

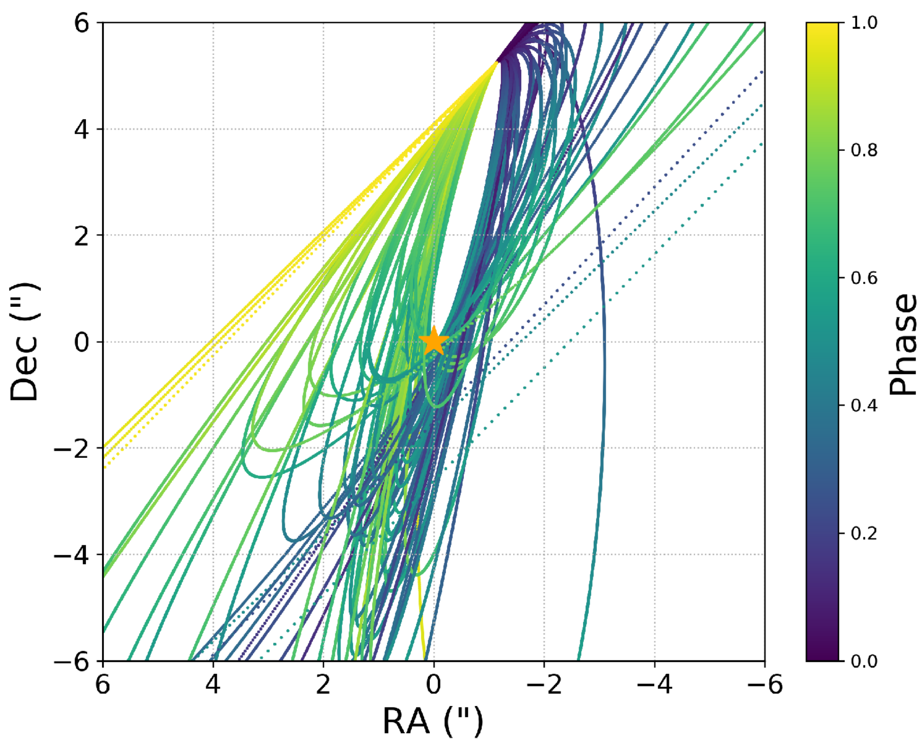


orbits.png

In [12]:

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

```
<IPython.core.display.Javascript object>
```

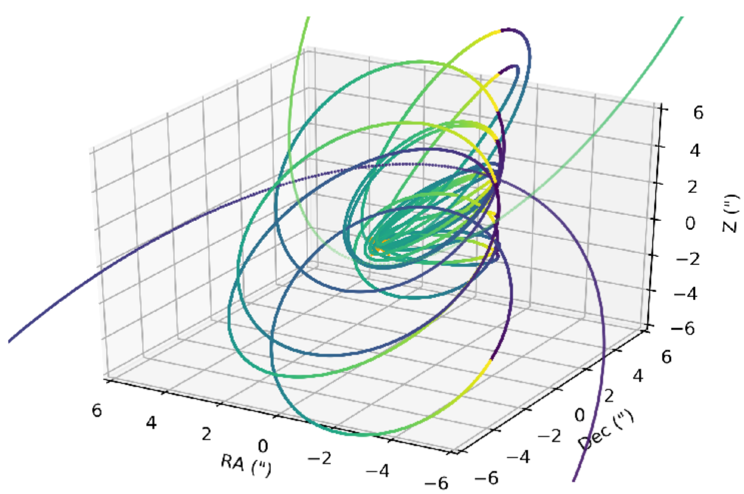


orbits_3d.png

In [13]:

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

```
<IPython.core.display.Javascript object>
```



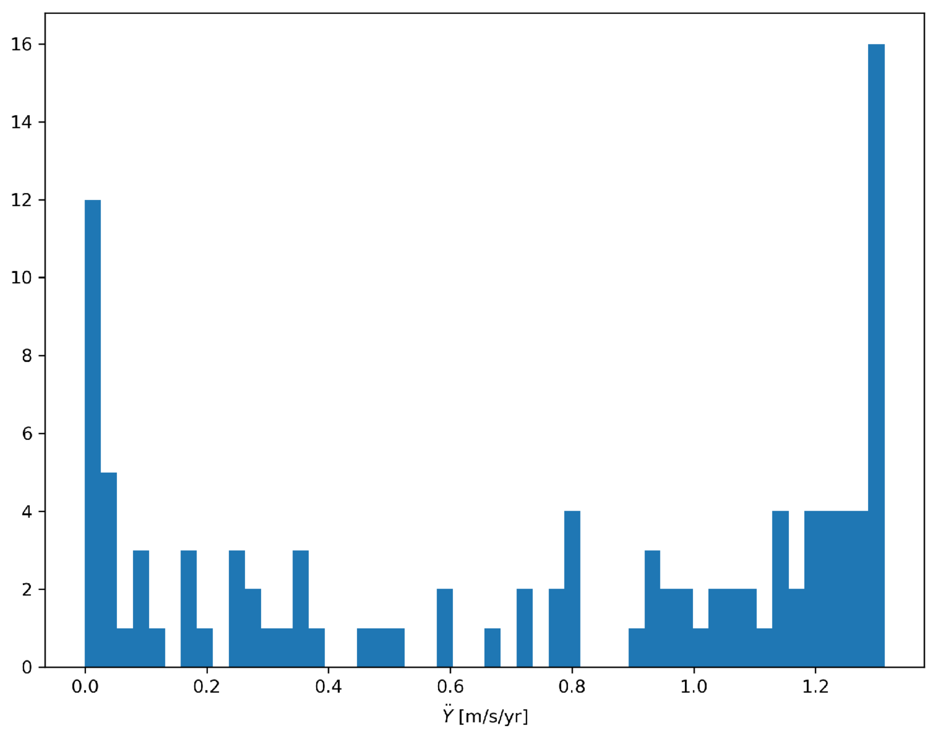
One of the observables posteriors:

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

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()
```

<IPython.core.display.Javascript object>



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_ (https://gea.esac.esa.int/archive/documentation/GDR2/Gaia_archive/chap_datamodel/sec_dm_main_](https://gea.esac.esa.int/archive/documentation/GDR2/Gaia_archive/chap_datamodel/sec_dm_main_) 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 +/- 0.24103006406237912
Total plane-of-sky relative velocity [mas/yr]: 15.03161860446753 +/- 1.50
86728000824803

sep,err [mas] 1837.4412911195748 0.34862183330431934 pa,err [deg]: 72.763
81454087225 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. This
indicates
            that the source might be an unresolved binary or experiencing
acceleration
            during the observation.  Orbit fit results may not be trustwo
rthy.  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 [ ]:
```

```