Example_code

February 28, 2020

[1]:
```
import os
os.environ['THEANO_FLAGS'] = 'optimizer_including=cudnn, force_device=True,␣
 ↪mode=FAST_RUN, device=cuda*,linker=cvm, optimizer=fast_compile'
```

[1]:
```
import astropy.io.fits as fits
import numpy as np
import matplotlib.pyplot as plt
import theano
import theano.tensor as tt
from theano.tensor import fft
import pymc3 as pm
from pymc3.variational.callbacks import CheckParametersConvergence
import theano.tensor.signal.conv
import exoplanet as xo
import scipy.signal
```

1 Interpolation function needed for model

[27]:
```
#Interpolation function used in model to obtain comparison points with data
def interpolate(x0, y0, x):
    x = np.array(x)
    idx = np.searchsorted(x0, x)
    dl = np.array(x - x0[idx - 1])
    dr = np.array(x0[idx] - x)
    d = dl + dr
    wl = dr / d
    return wl * y0[idx - 1] + (1 - wl) * y0[idx]
```

2 Specify simple model

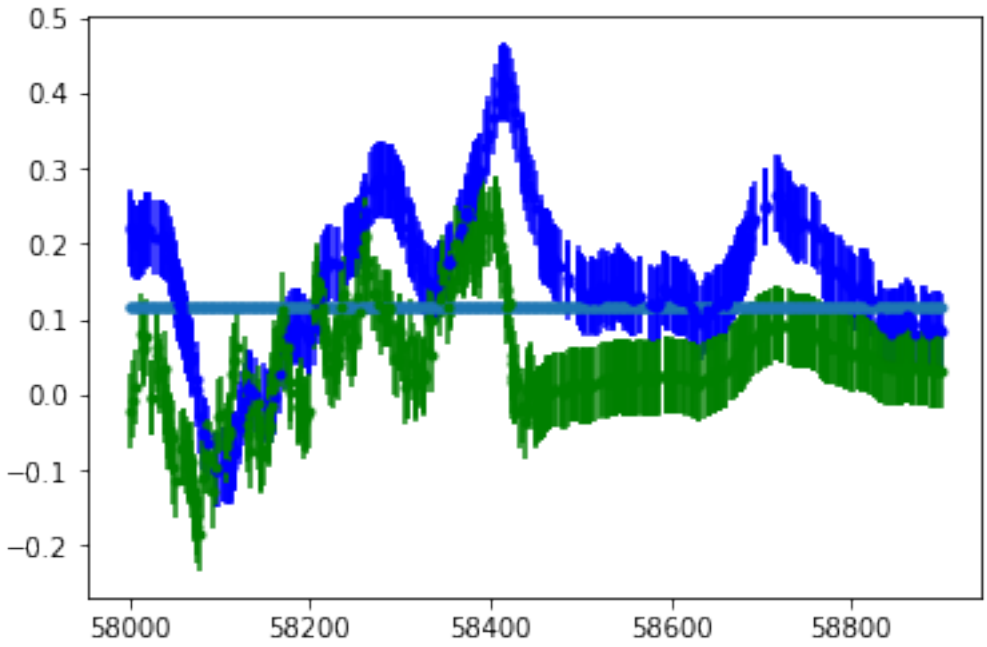
[48]:
```
import random
#Load in synthetic data
yK,yKerr = np.loadtxt('Kband.txt', delimiter=',', usecols=(0,1), unpack=True)
yi,yierr = np.loadtxt('iband.txt', delimiter=',', usecols=(0,1), unpack=True)
yg,ygerr = np.loadtxt('gband.txt', delimiter=',', usecols=(0,1), unpack=True)
```

```
X=np.linspace(58000,58900,5000)
yKerr=np.ones(len(yKerr))*max(yKerr)
yierr=np.ones(len(yierr))*max(yierr)
#Select points at random
n_list = 499# Number of selected points
the_list = list(range(len(X)))
ind = random.sample(the_list, n_list)
ind2 = random.sample(the_list, n_list)
yK=yK[ind]
yKerr=yKerr[ind]
XK=X[ind]
yi=yi[ind2]
yierr=yierr[ind2]
Xi=X[ind2]
```

[49]:
```
nf = 499 #Number of GP points
Xf = np.linspace(np.min([XK,Xi])-1.0, np.max([XK,Xi])+1.0,nf)
Xf=np.reshape(Xf,(len(Xf),1))
tau=np.linspace(1.0,100.0,nf)
```

[50]:
```
plt.plot(Xf,2e-6*Xf,'.')
plt.errorbar(XK, yK, yKerr, fmt='b.', label='K')
plt.errorbar(Xi, yi, yierr, fmt='g.', label='i')
```

[50]: <ErrorbarContainer object of 3 artists>



[51]:
```
#Define prior range
mlow=2.3
mhigh=3.7
mmu=(mhigh+mlow)/2.0
msig=(mhigh-mlow)/2.0
siglow=0.1
sighigh=2.55
sigmu=(sighigh+siglow)/2.0
sigsig=(sighigh-siglow)/2.0
```

[28]:
```
with pm.Model() as convmodel:
    ##############################################
    #define driving function as Gaussian Process
    ##############################################

     = pm.Bound(pm.Normal, lower=0.0,upper=0.71)(' ', mu=0.355, sigma=0.
↪355)#timescale of variation for the driving function, order of days for UV
    #REMEMBER time scale is 2* ~2 so remember to rewrite as _true=2* ~2
     = pm.Bound(pm.Normal, lower=0.0,upper=0.4)(' ', mu=0.2, sigma=0.2)#long␣
↪term standard deviation for the driving function
    cov =  **2 * pm.gp.cov.Exponential(1, ls= )#using same cov as light curve␣
↪interpolation
    gp = pm.gp.Latent(cov_func=cov)
    f = gp.prior("f", X=Xf,reparameterize = False)
    f = f.reshape((1,1,len(Xf),1))

    ###############
    #Define priors
    ###############
    #Universal Dusty Torus parameters for the uniform temperature DT
    sigma_DT=pm.Bound(pm.Normal, lower=siglow,upper=sighigh)('sigma_DT',␣
↪mu=sigmu, sigma=sigsig)#needs a source for scale
    m_DT=pm.Bound(pm.Normal, lower=mlow,upper=mhigh)('m_DT', mu=mmu,␣
↪sigma=msig)#we expect serveral tens to hundreds of days from the nature␣
↪letter
    theta_DT=pm.Bound(pm.Normal, lower=2.3,upper=4.1)('theta_DT', mu=3.
↪2,sigma=0.9)#add later when simple model is staple
    #Accretion Disk paramters
    #K band
    Ksigma_AD=pm.Bound(pm.Normal, lower=siglow,upper=sighigh)('Ksigma_AD',␣
↪mu=sigmu, sigma=sigsig)# Shappee 2014 suggests somewhere between 0-20 days␣
↪so log that
    Ktheta_AD=0.0#pm.Normal('Ktheta_AD',mu=0.0,sigma=10.0)#add later
    Km_AD=pm.Bound(pm.Normal, lower=mlow,upper=mhigh)('Km_AD', mu=mmu,␣
↪sigma=msig)#AD has 3-5 times smaller lags than DT
    #i band
```

```
   isigma_AD=pm.Bound(pm.Normal, lower=siglow,upper=sighigh)('isigma_AD',␣
↪mu=sigmu, sigma=sigsig)# Shappee 2014 suggests somewhere between 0-20 days␣
↪so log that
   itheta_AD=0.0#pm.Normal('gtheta_AD',mu=0.0,sigma=10.0)#add later
   im_AD=pm.Bound(pm.Normal, lower=mlow,upper=mhigh)('im_AD', mu=mmu,␣
↪sigma=msig)#AD has 3-5 times smaller lags than DT
   #BB and power law parameters
   T=pm.Bound(pm.Normal, lower=6.90775527898 ,upper=7.74066440192)('T',mu=7.
↪32420984045,sigma=0.41645456146)#taken from nature letter
   K_0=pm.Bound(pm.Normal, lower=-2.3,upper=2.3)('K_0', mu=0, sigma=2.3)#powr/
↪BB
   index=pm.Bound(pm.Normal, lower=0.5,upper=3.0)('index', mu=1.5, sigma=0.
↪5)#sign depends on diffmag definition change to -2 to -1
   #Note for index: we have taken the transformation from F_nu to F_lamb into␣
↪account with the index value.

   ##############
   #Define model
   ##############

   #Peak Black Body from uniform torus temperature
   BB_max = -79.3575 + 5.0*T#the log of the peak wavelength blackbody

   #Universal lognormal for Dusty Torus
   exp_DT = -((tt.log((tau-tt.exp(theta_DT))/tt.exp(m_DT)))**2/(2*sigma_DT**2))
   front_DT = 1.0/((tau-tt.exp(theta_DT))*sigma_DT*tt.sqrt(2*np.pi))
   lognorm_DT = front_DT*tt.exp(exp_DT)
   lognorm_DT = tt.switch(tt.isnan(lognorm_DT), 0.0, lognorm_DT)

   #Dusty Torus transfer equation for K band
   Kb = 6692.0/tt.exp(T)
   KBB = -38.36611560560854-tt.log(tt.exp(Kb) - 1.0)
   KPsi_DT = (tt.exp(KBB)/tt.exp(BB_max))*lognorm_DT
   #Dusty Torus transfer equation for i band
   ib = 18690.0/tt.exp(T)
   iBB = -33.230653704248226-tt.log(tt.exp(ib) - 1.0)
   iPsi_DT = (tt.exp(iBB)/tt.exp(BB_max))*lognorm_DT

   #Accretion Disk transfer equation for the K band
   Kpowr = K_0+0.649998592333457*index
   Kexp_AD = -((tt.log((tau-Ktheta_AD)/tt.exp(Km_AD)))**2/(2*Ksigma_AD**2))
   Kfront_AD = 1.0/((tau-Ktheta_AD)*Ksigma_AD*tt.sqrt(2*np.pi))
   Klognorm_AD = Kfront_AD*tt.exp(Kexp_AD)
   KPsi_AD = tt.exp(Kpowr)*Klognorm_AD
   #Accretion Disk transfer equation for the i band
   ipowr = K_0-0.3770937879386054*index
```

```
    iexp_AD = -((tt.log((tau-itheta_AD)/tt.exp(im_AD)))**2/(2*isigma_AD**2))
    ifront_AD = 1.0/((tau-itheta_AD)*isigma_AD*tt.sqrt(2*np.pi))
    ilognorm_AD = ifront_AD*tt.exp(iexp_AD)
    iPsi_AD = tt.exp(ipowr)*ilognorm_AD

    ##########################
    #Full transfer equations
    ##########################

    Ktransfer = KPsi_DT + KPsi_AD
    Ktransfer = Ktransfer.reshape(((1,1,len(tau),1)))
    itransfer = iPsi_DT + iPsi_AD
    itransfer = itransfer.reshape(((1,1,len(tau),1)))

    #The convolutions
    ########################################################################
    #'half': pad input with a symmetric border of filter rows // 2
    #rows and filter columns // 2 columns, then perform a valid convolution.
    #For filters with an odd number of rows and columns,
    #this leads to the output shape being equal to the input shape.
    ########################################################################

    Kconvol=theano.tensor.nnet.conv2d(f,Ktransfer,border_mode='half')
    Kcomp=interpolate(Xf[:,0],Kconvol[0,0,:,0],XK)
    iconvol=theano.tensor.nnet.conv2d(f,itransfer,border_mode='half')
    icomp=interpolate(Xf[:,0],iconvol[0,0,:,0],Xi)

    ####################
    #Define likelihoods
    ####################

    Klikelihood = pm.Normal('yK', mu=Kcomp, sigma=yKerr, observed=yK)
    ilikelihood = pm.Normal('yi', mu=icomp, sigma=yierr, observed=yi)

    #the shape of mu and observed needs to be the same
    ########################################################################
    #max_treedepth, default=10
    #The maximum tree depth. Trajectories are stopped when this depth is␣
↪reached.
    #early_max_treedepth, default=8
    #The maximum tree depth during the first 200 tuning samples.
    ########################################################################

    tracetransfer = pm.sample(2000,tune=2000,init='advi+adapt_diag',chains=2)
```

```
Auto-assigning NUTS sampler…
Initializing NUTS using advi+adapt_diag…
```

```
  0%|          | 0/200000 [00:00<?,
?it/s]/home/malte/anaconda3/lib/python3.7/site-
packages/theano/tensor/basic.py:6611: FutureWarning: Using a non-tuple sequence
for multidimensional indexing is deprecated; use `arr[tuple(seq)]` instead of
`arr[seq]`. In the future this will be interpreted as an array index,
`arr[np.array(seq)]`, which will result either in an error or a different
result.
  result[diagonal_slice] = x
Average Loss = -227.7:  12%|         | 23595/200000 [02:49<21:08, 139.06it/s]
Convergence achieved at 23600
Interrupted at 23,599 [11%]: Average Loss = 427.51
/home/malte/anaconda3/lib/python3.7/site-packages/theano/tensor/basic.py:6611:
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deprecated; use `arr[tuple(seq)]` instead of `arr[seq]`. In the future this will
be interpreted as an array index, `arr[np.array(seq)]`, which will result either
in an error or a different result.
  result[diagonal_slice] = x
Multiprocess sampling (2 chains in 4 jobs)
NUTS: [index, K_0, T, im_AD, isigma_AD, Km_AD, Ksigma_AD, theta_DT, m_DT,
sigma_DT, f,  , ]
Sampling 2 chains, 0 divergences: 100%|     | 8000/8000 [12:54:30<00:00,
5.81s/draws]
The acceptance probability does not match the target. It is 0.8935700370159257,
but should be close to 0.8. Try to increase the number of tuning steps.
The chain reached the maximum tree depth. Increase max_treedepth, increase
target_accept or reparameterize.
The chain reached the maximum tree depth. Increase max_treedepth, increase
target_accept or reparameterize.
The rhat statistic is larger than 1.4 for some parameters. The sampler did not
converge.
```
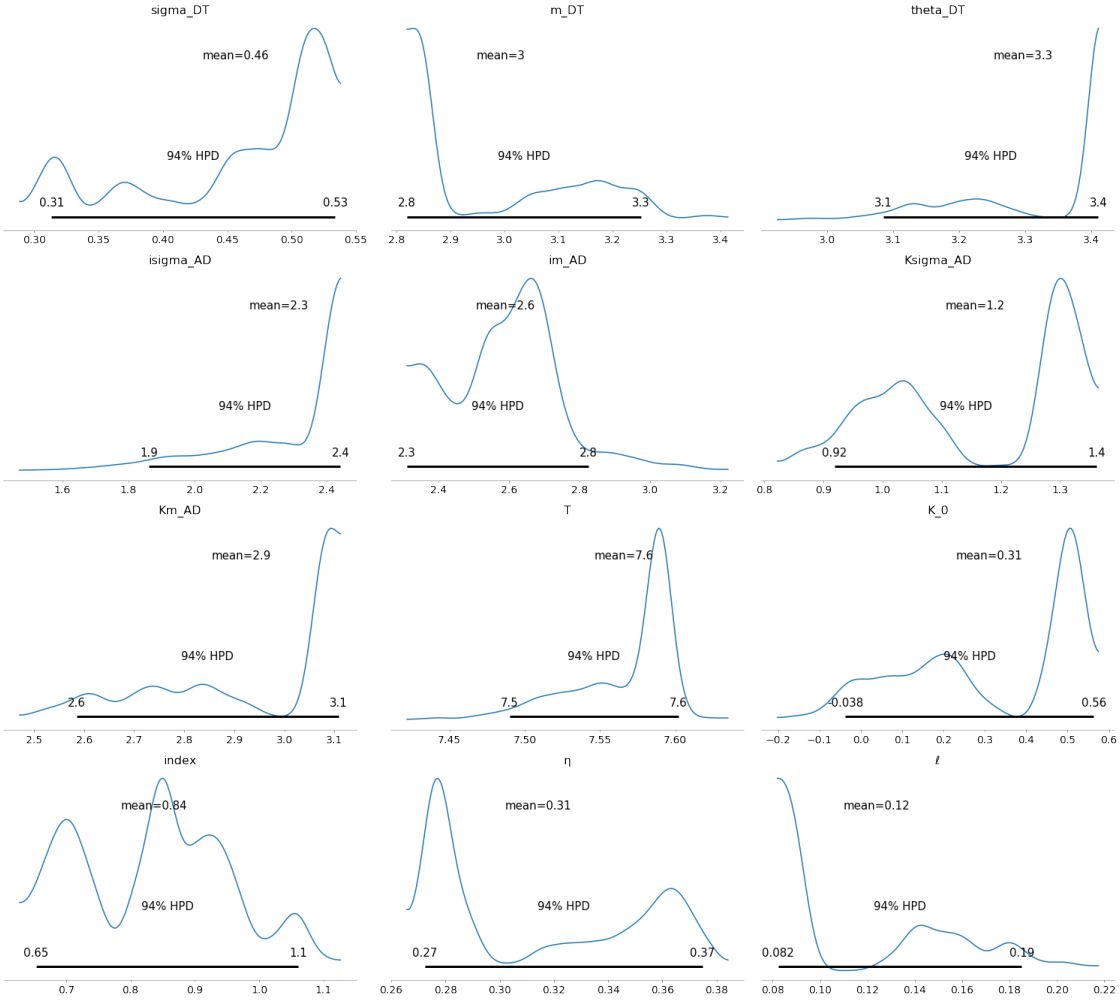

The estimated number of effective samples is smaller than 200 for some parameters.

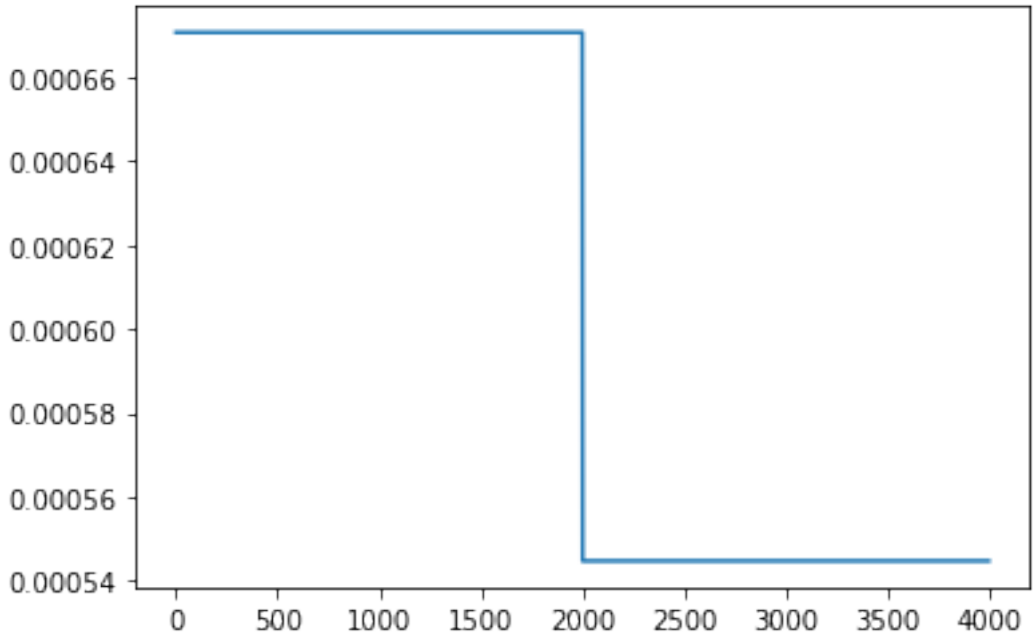
[29]:
```
tracesimple=tracetransfer
simplenames=['sigma_DT','m_DT','theta_DT','isigma_AD','itheta_AD','im_AD','Ksigma_AD','Ktheta_
 ↪' ', ' ']
simplenames=['sigma_DT','m_DT','theta_DT','isigma_AD','im_AD','Ksigma_AD','Km_AD','T','K_0','i
 ↪' ', ' ']
pm.plot_posterior(tracesimple, simplenames);
```



3 Sampler convergence statistics

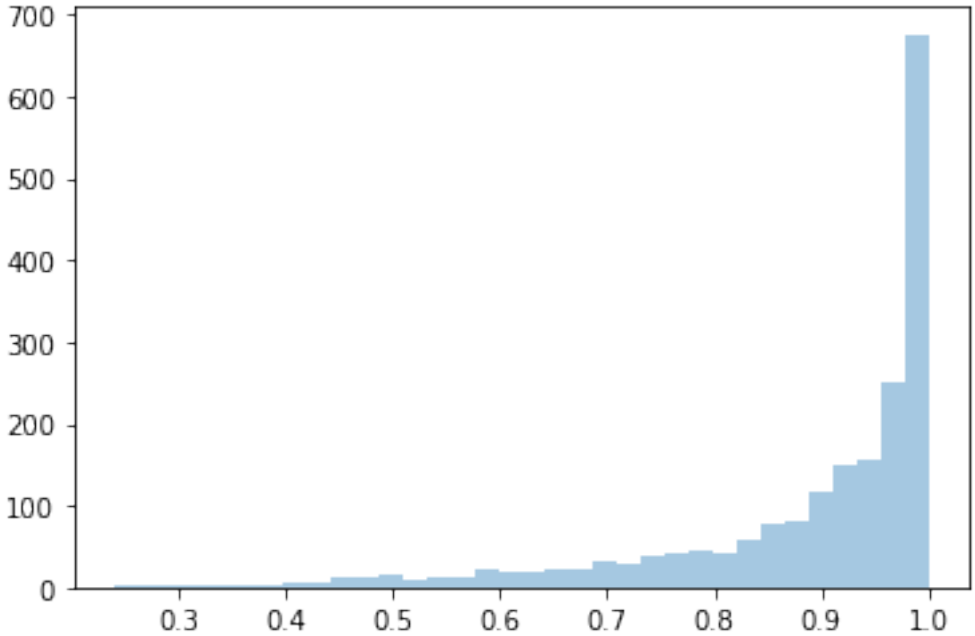
[30]:
```
plt.plot(tracesimple['step_size_bar'])
```

[30]: [<matplotlib.lines.Line2D at 0x7fbb41d83f90>]



[31]:
```
import seaborn as sb
accept = tracesimple.get_sampler_stats('mean_tree_accept', burn=1000)
sb.distplot(accept, kde=False)
```

[31]: <matplotlib.axes._subplots.AxesSubplot at 0x7fbb4155e6d0>

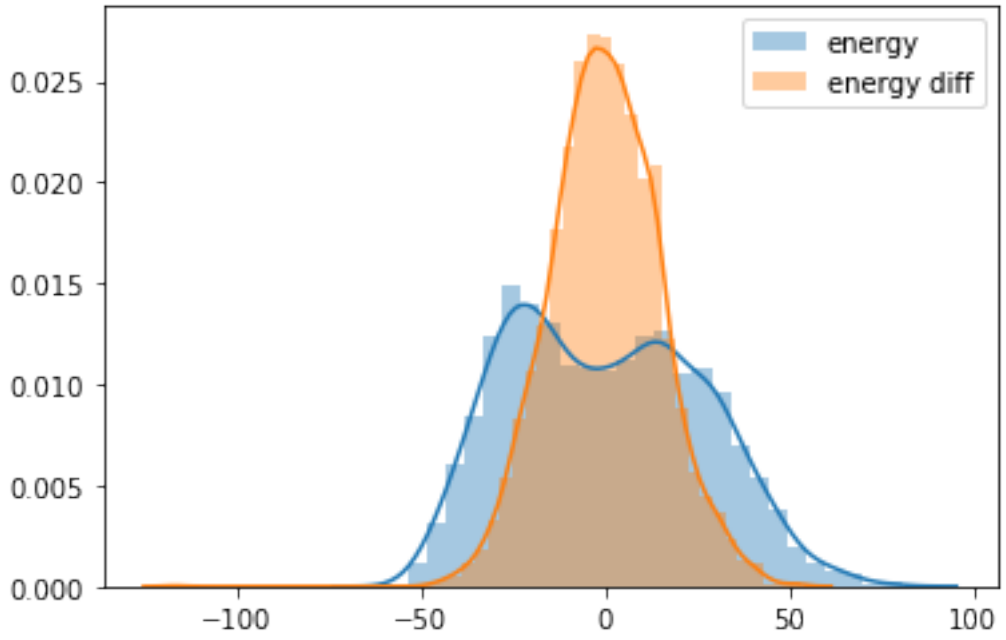


[56]:
```
tracesimple['diverging'].nonzero()
```

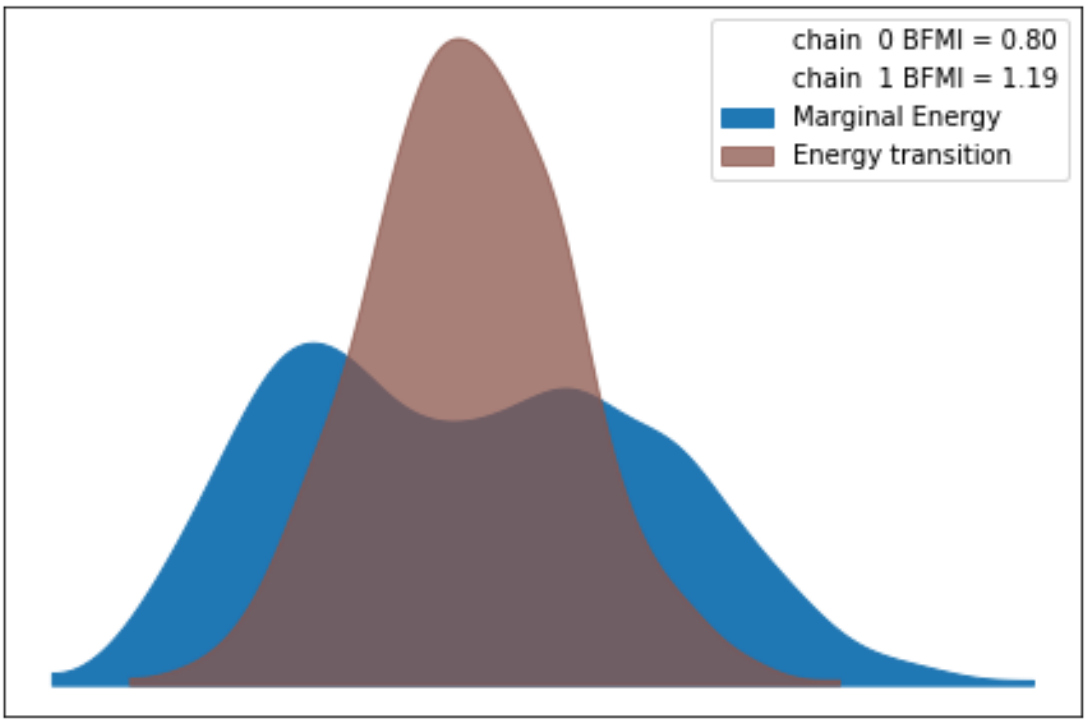
[56]:
```
(array([], dtype=int64),)
```

[32]:
```
energy = tracesimple['energy']
energy_diff = np.diff(energy)
sb.distplot(energy - energy.mean(), label='energy')
sb.distplot(energy_diff, label='energy diff')
plt.legend()
```

[32]:
```
<matplotlib.legend.Legend at 0x7fbb424ea150>
```



[33]:
```
pm.energyplot(tracesimple);
```



4 Sampler results

[34]:
```
summ=pm.summary(tracesimple,simplenames)
#print(summ.loc[:,'mean'])
summ
```

[34]:

	mean	sd	hpd_3%	hpd_97%	mcse_mean	mcse_sd	ess_mean	\
sigma_DT	0.457	0.074	0.313	0.534	0.050	0.042	2.0	
m_DT	2.994	0.166	2.820	3.253	0.112	0.092	2.0	
theta_DT	3.296	0.128	3.085	3.410	0.087	0.073	2.0	
isigma_AD	2.254	0.205	1.862	2.441	0.118	0.096	3.0	
im_AD	2.589	0.155	2.311	2.827	0.027	0.020	32.0	
Ksigma_AD	1.157	0.158	0.919	1.362	0.107	0.090	2.0	
Km_AD	2.915	0.190	2.585	3.108	0.121	0.100	2.0	
T	7.566	0.035	7.490	7.602	0.017	0.013	4.0	
K_0	0.310	0.208	-0.038	0.563	0.137	0.120	2.0	
index	0.837	0.118	0.654	1.061	0.067	0.053	3.0	
	0.314	0.038	0.272	0.375	0.025	0.021	2.0	
	0.124	0.039	0.082	0.185	0.027	0.022	2.0	

	ess_sd	ess_bulk	ess_tail	r_hat
sigma_DT	2.0	3.0	12.0	2.22

```
m_DT          2.0      2.0      11.0   2.47
theta_DT      2.0      2.0      19.0   2.78
isigma_AD     3.0      3.0      11.0   2.29
im_AD        32.0     29.0      76.0   1.29
Ksigma_AD     2.0      3.0      14.0   2.23
Km_AD         2.0      3.0      21.0   1.85
T             4.0      4.0      55.0   1.85
K_0           2.0      3.0      12.0   2.02
index         3.0      3.0      11.0   1.62
             2.0      3.0      35.0   1.86
             2.0      2.0      11.0   2.78
```

[35]:
```
pm.traceplot(tracesimple, var_names=simplenames);
```

```
/home/malte/.local/lib/python3.7/site-
packages/arviz/plots/backends/matplotlib/distplot.py:38: UserWarning: Argument
backend_kwargs has not effect in matplotlib.plot_distSupplied value won't be
used
  "Argument backend_kwargs has not effect in matplotlib.plot_dist"
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packages/arviz/plots/backends/matplotlib/distplot.py:38: UserWarning: Argument
backend_kwargs has not effect in matplotlib.plot_distSupplied value won't be
used
  "Argument backend_kwargs has not effect in matplotlib.plot_dist"
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backend_kwargs has not effect in matplotlib.plot_distSupplied value won't be
used
  "Argument backend_kwargs has not effect in matplotlib.plot_dist"
```
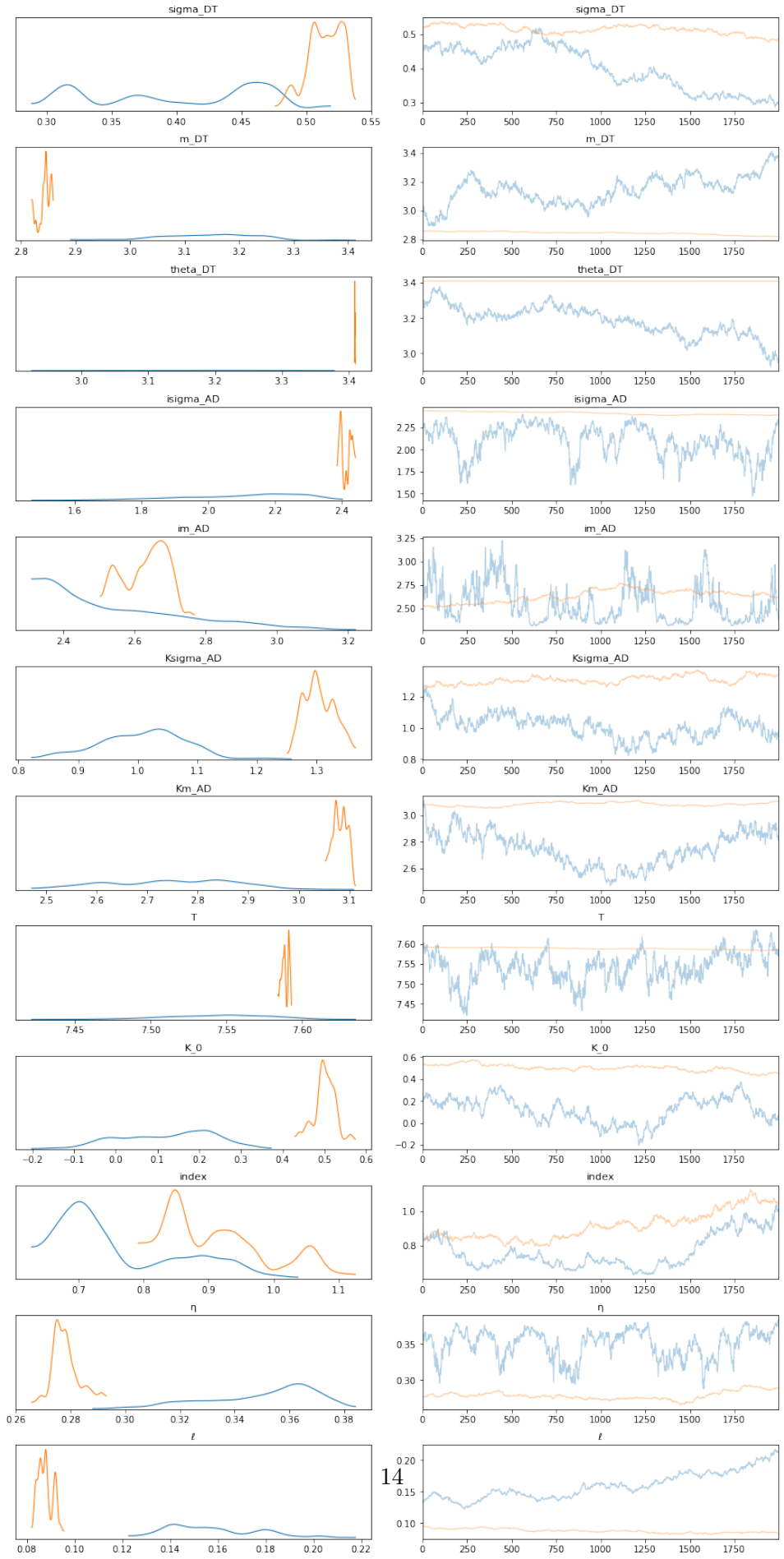
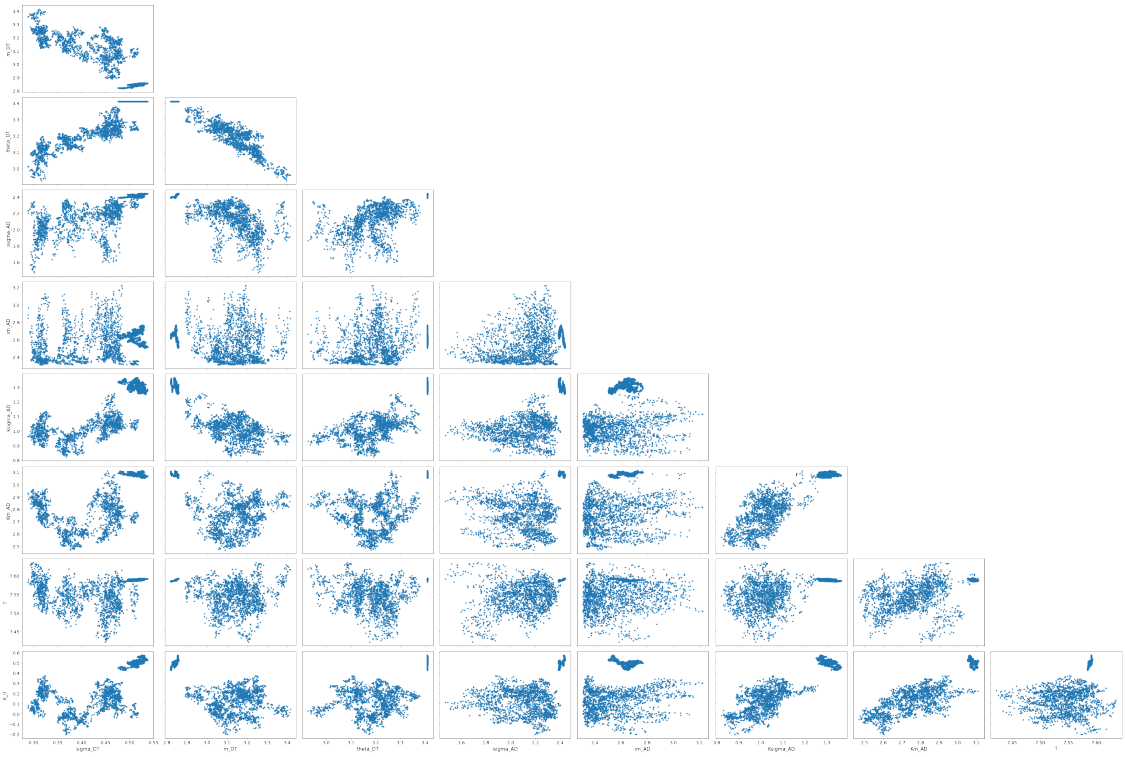


sigma_DT
m_DT
theta_DT
isigma_AD
im_AD
Ksigma_AD
Km_AD
T
K_0
index
η
ℓ

[36]:
```
pm.pairplot(tracesimple, var_names=simplenames, divergences=True);
```

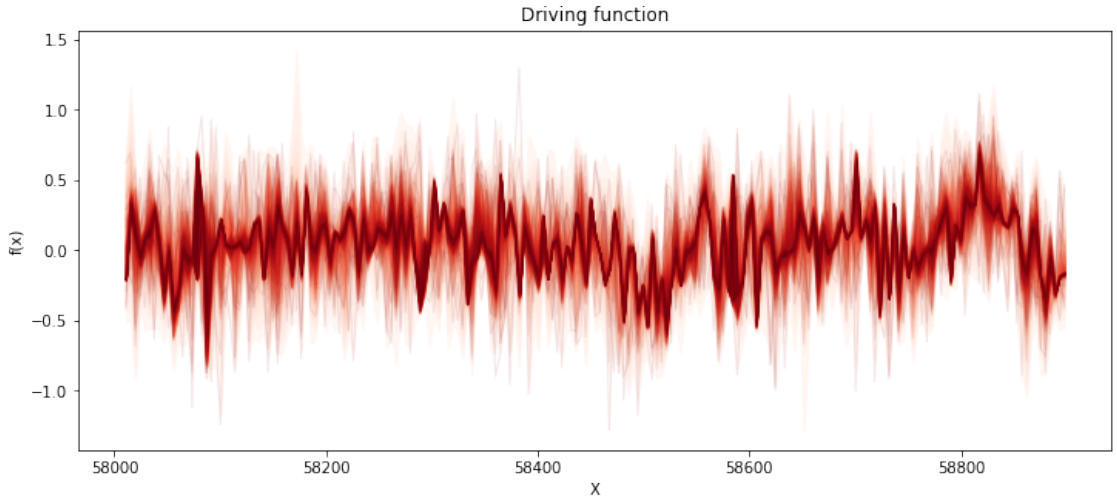
```
/home/malte/.local/lib/python3.7/site-
packages/arviz/plots/backends/matplotlib/pairplot.py:90: SyntaxWarning:
rcParams['plot.max_subplots'] (40) is smaller than the number of resulting pair
plots with these variables, generating only a 9x9 grid
  SyntaxWarning,
```



5 GP and conditional GP

[37]:
```
# plot the results
fig = plt.figure(figsize=(12,5)); ax = fig.gca()

# plot the samples from the gp posterior with samples and shading
from pymc3.gp.util import plot_gp_dist
plot_gp_dist(ax, tracetransfer["f"], Xf);
#plot_gp_dist(ax, resu["f"], Xf);
# plot the data and the true latent function
#plt.plot(X, y, 'ok', ms=3, alpha=0.5, label="Observed data");
```

```
# axis labels and title
plt.xlabel("X"); plt.ylabel("f(x)");
plt.title("Driving function");
```



[38]:
```
n_new = 1000
X_new = np.linspace(min(Xf), max(Xf), n_new)

# add the GP conditional to the model, given the new X values
with convmodel:
    f_J = gp.conditional("f_J", X_new)

# Sample from the GP conditional distribution
with convmodel:
    pred_samples = pm.sample_posterior_predictive(tracesimple, vars=[f_J],␣
 ↪samples=1000)
```

```
/home/malte/.local/lib/python3.7/site-packages/pymc3/sampling.py:1247:
UserWarning: samples parameter is smaller than nchains times ndraws, some draws
and/or chains may not be represented in the returned posterior predictive sample
  "samples parameter is smaller than nchains times ndraws, some draws "
100%|      | 1000/1000 [09:58<00:00,  1.67it/s]
```

[39]:
```
#Calculate the mean and standard deviation of the traces.
mu = np.zeros(len(X_new))
sd = np.zeros(len(X_new))

for i in range(0,len(X_new)):
    mu[i] = np.mean(pred_samples["f_J"][:,i])
    sd[i] = np.std(pred_samples["f_J"][:,i])
```

```
# draw plot
fig = plt.figure(figsize=(12,5)); ax = fig.gca()

# plot mean and 1  intervals
plt.plot(X_new, mu, 'r', lw=2, label="mean and 1  region");
plt.plot(X_new, mu + 1*sd, 'r', lw=1); plt.plot(X_new, mu - 1*sd, 'r', lw=1);
plt.fill_between(X_new.flatten(), mu - 1*sd, mu + 1*sd, color="r", alpha=0.5)
#plt.errorbar(XJ,mu,sd,fmt='r.',label='Driving function value at data points')

# plot original data and true function
#plt.plot(X, y, 'ok', ms=3, alpha=1.0, label="observed data")
#plt.errorbar(X, y, yerr,fmt='.',label="observed data")

plt.xlabel("t");
plt.ylabel("diffmag")
plt.title("predictive mean and 1  interval"); plt.legend();
print(np.mean(sd))
```

```
0.3430096292121166
```