Lecture 10

November 8, 2018

Lab 5 and 6

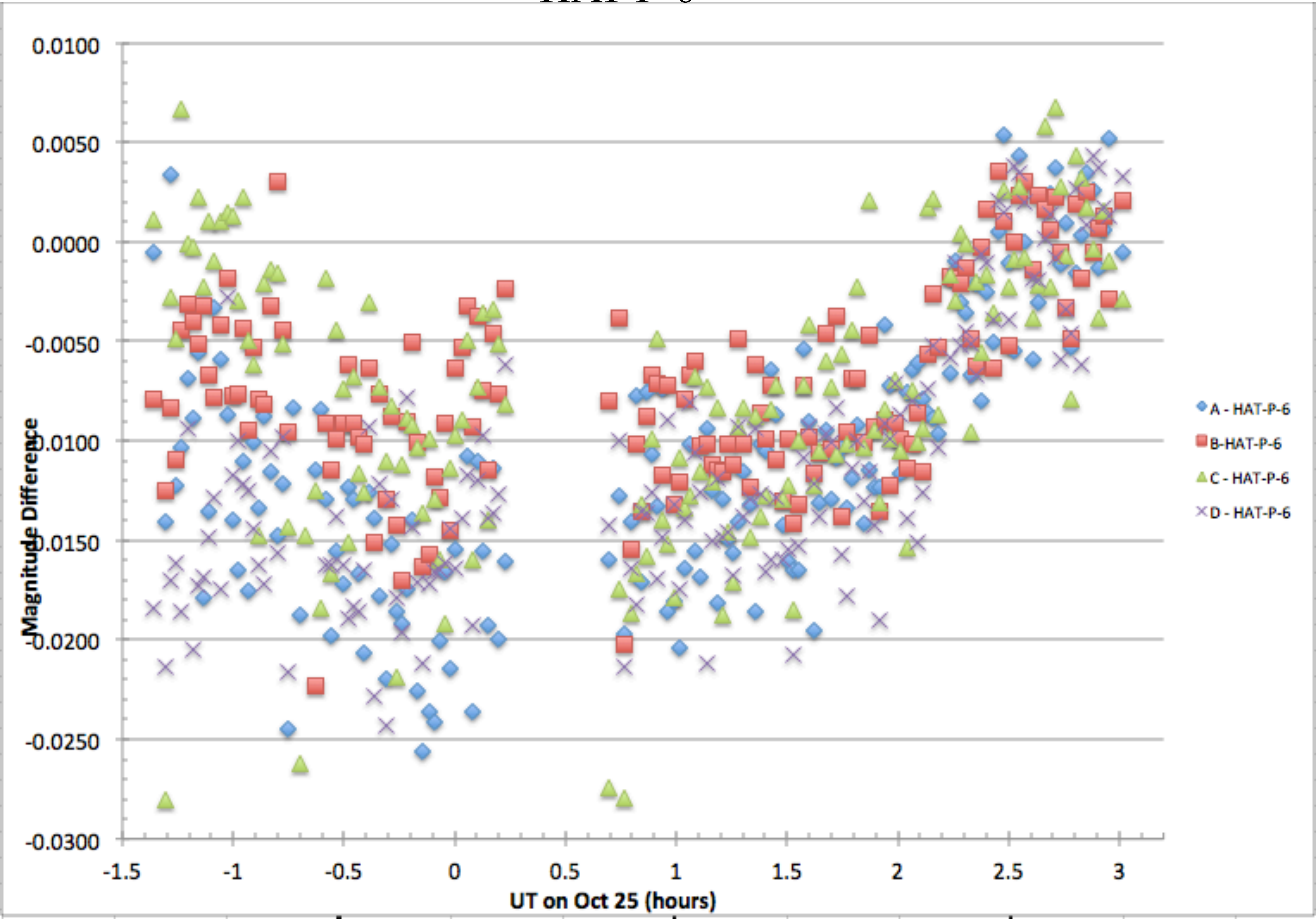
News

- Lab 3 and 4
  - Handed back next week (I hope).
- Lab 5 (Transiting Exoplanets)
  - Due: November 8 (today)
- Lab 6 (Color-Magnitude Diagram)
  - Observing starts on Friday
  - Email me your instrumental color-magnitude diagram by Wednesday, November 21
  - Entire lab due: November 29

Photometry in Images

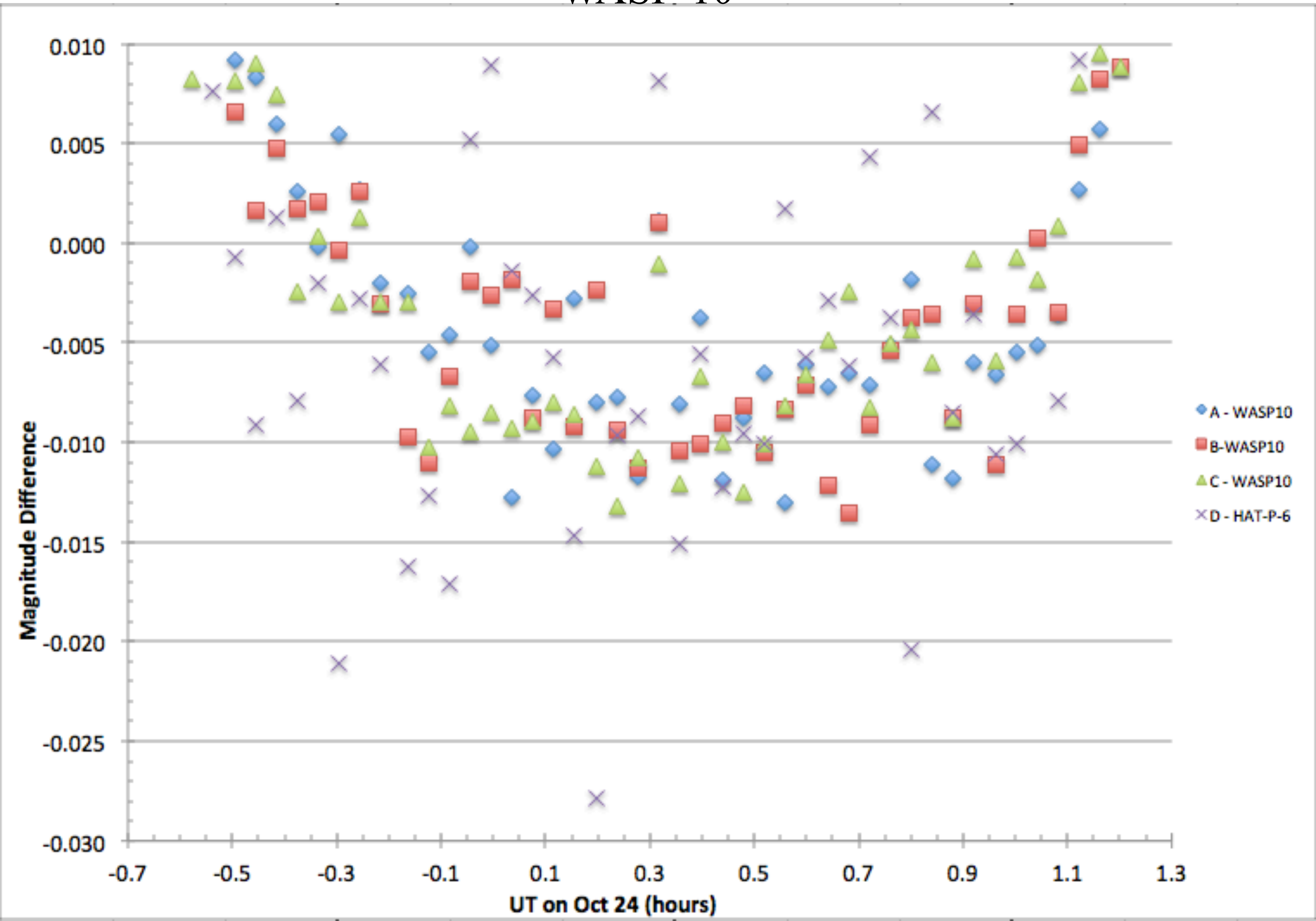
- Correct the image to a uniform, linear response.
  - Dark current and bias level subtraction either
    - done at the telescope with *autodark* subtraction or
    - done by taking separate dark images and subtracting them from the science images later.
  - Need to create an average image of a uniformly illuminated field ("flat field") and divide by it.
    - The mkflatru command.
- Identify your target and comparison stars.
- Measure the brightness of stars in all of the images.

HAT-P-6



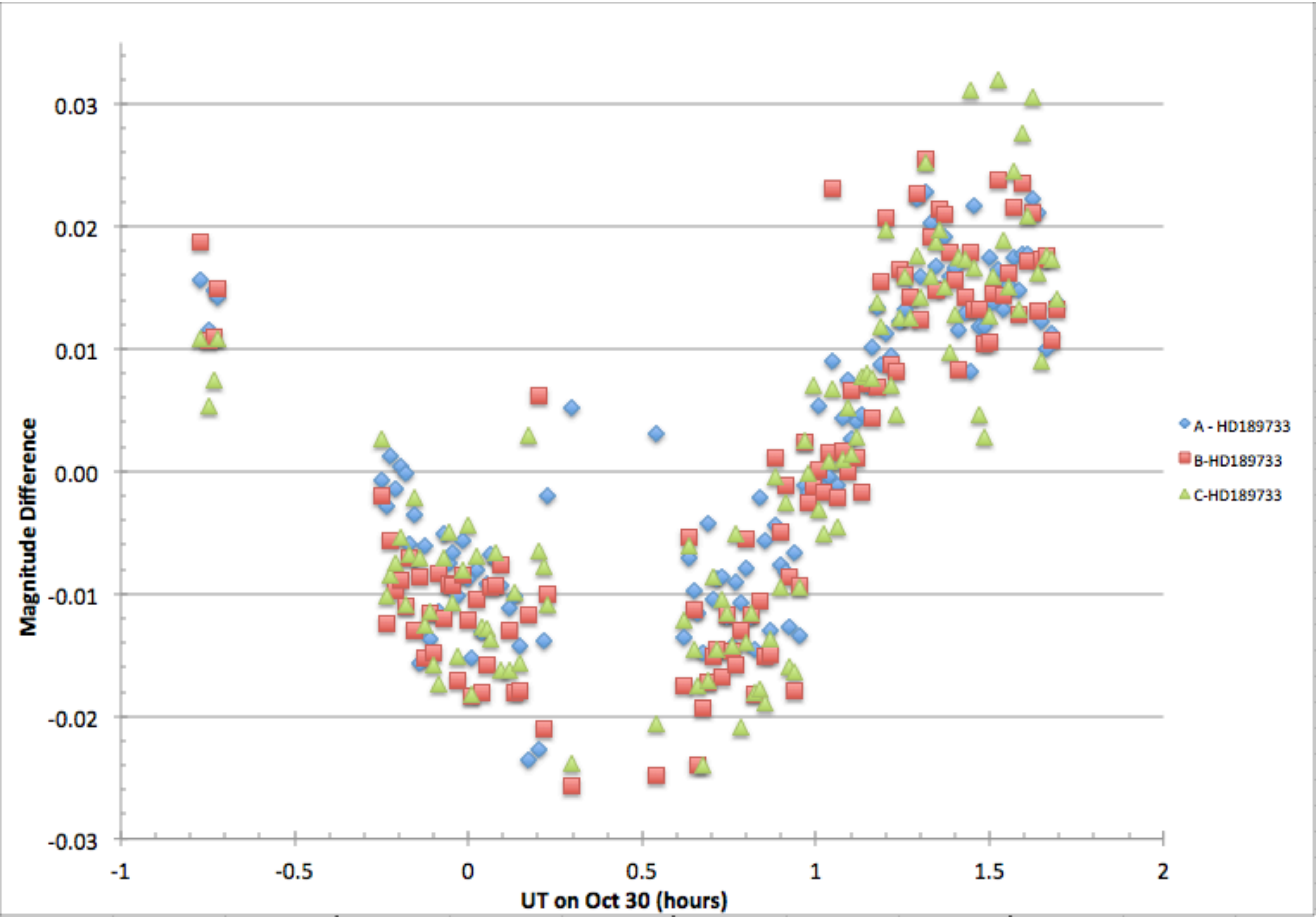
0.0100
0.0050
0.0000
-0.0050
-0.0100
-0.0150
-0.0200
-0.0250
-0.0300
Magnitude Difference
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
UT on Oct 25 (hours)
A - HAT-P-6
B-HAT-P-6
C - HAT-P-6
D - HAT-P-6

WASP-10



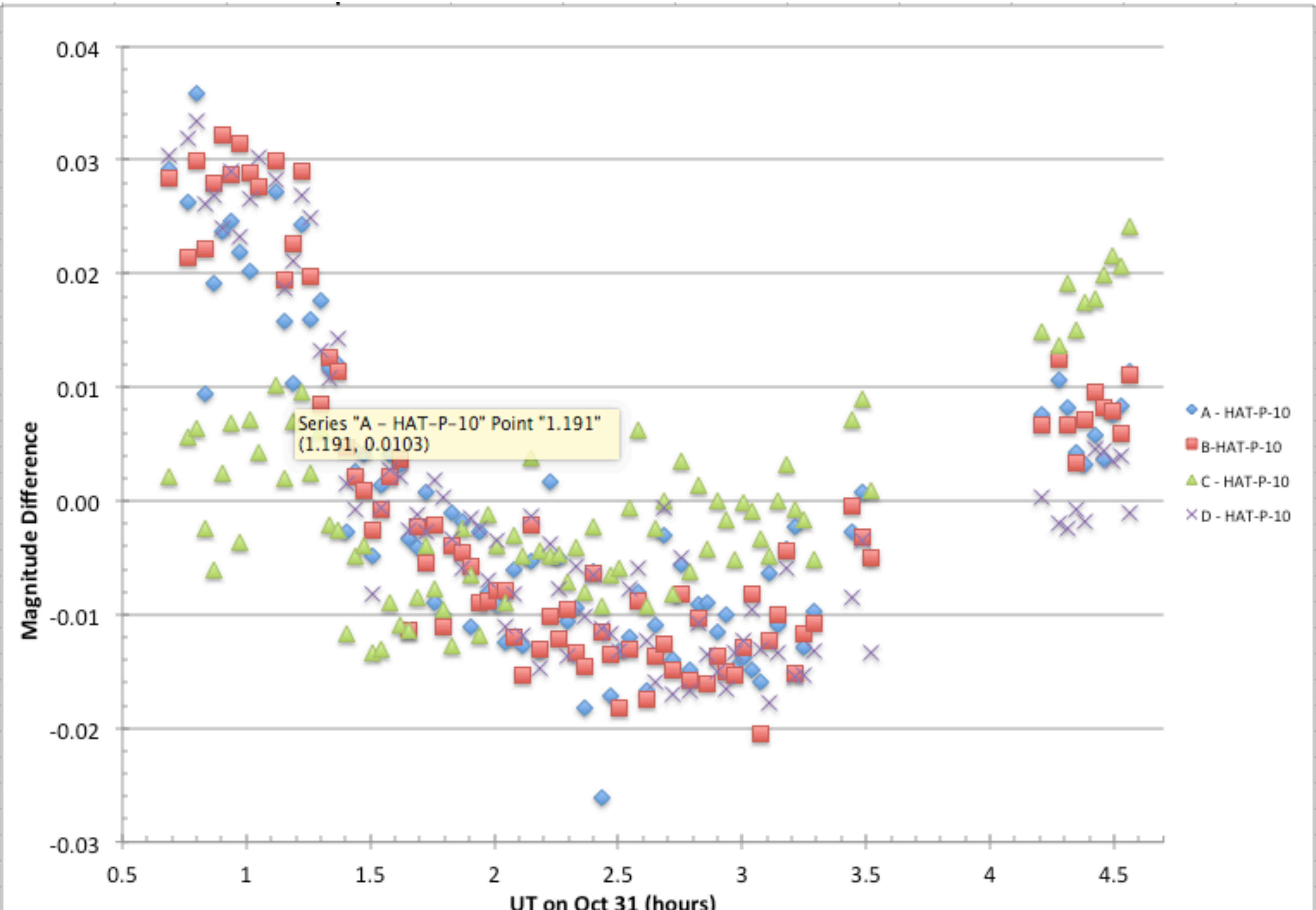
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
Magnitude Difference
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
UT on Oct 24 (hours)
A - WASP10
B-WASP10
C - WASP10
D - HAT-P-6

HD189733

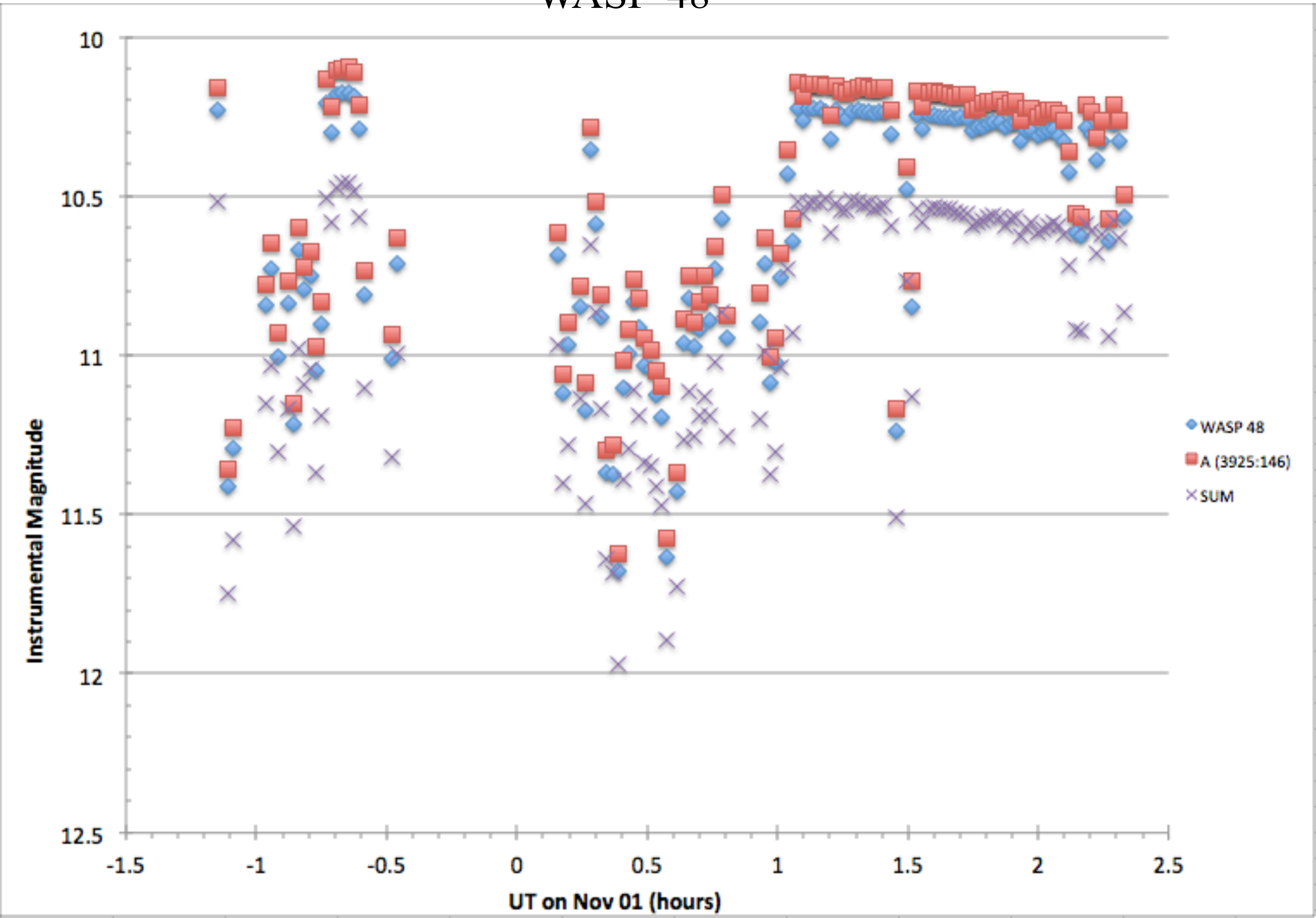


Magnitude Difference
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-1
-0.5
0
0.5
1
1.5
2
UT on Oct 30 (hours)
A - HD189733
B-HD189733
C-HD189733

HAT-P-10/WASP-11

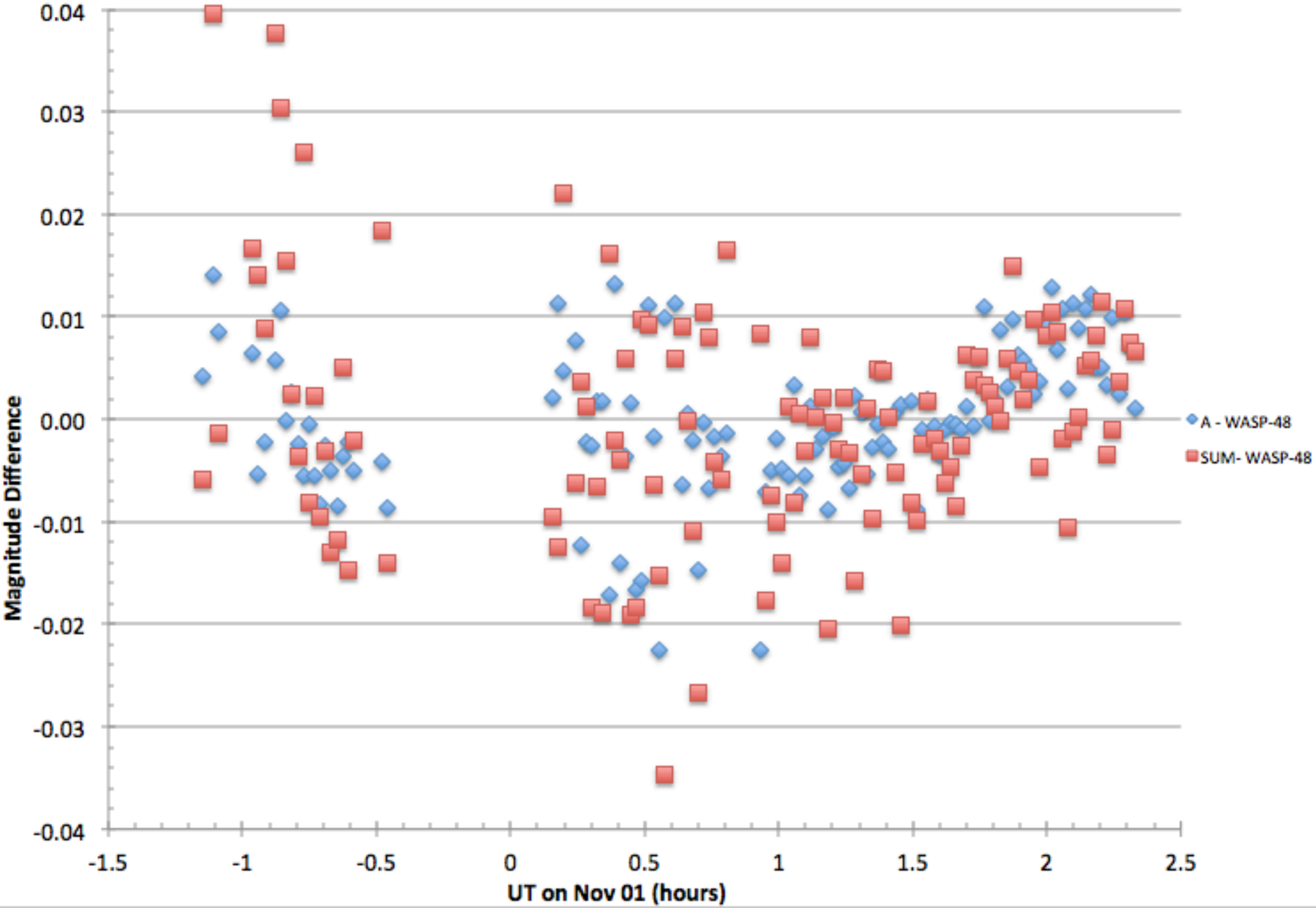


WASP-48



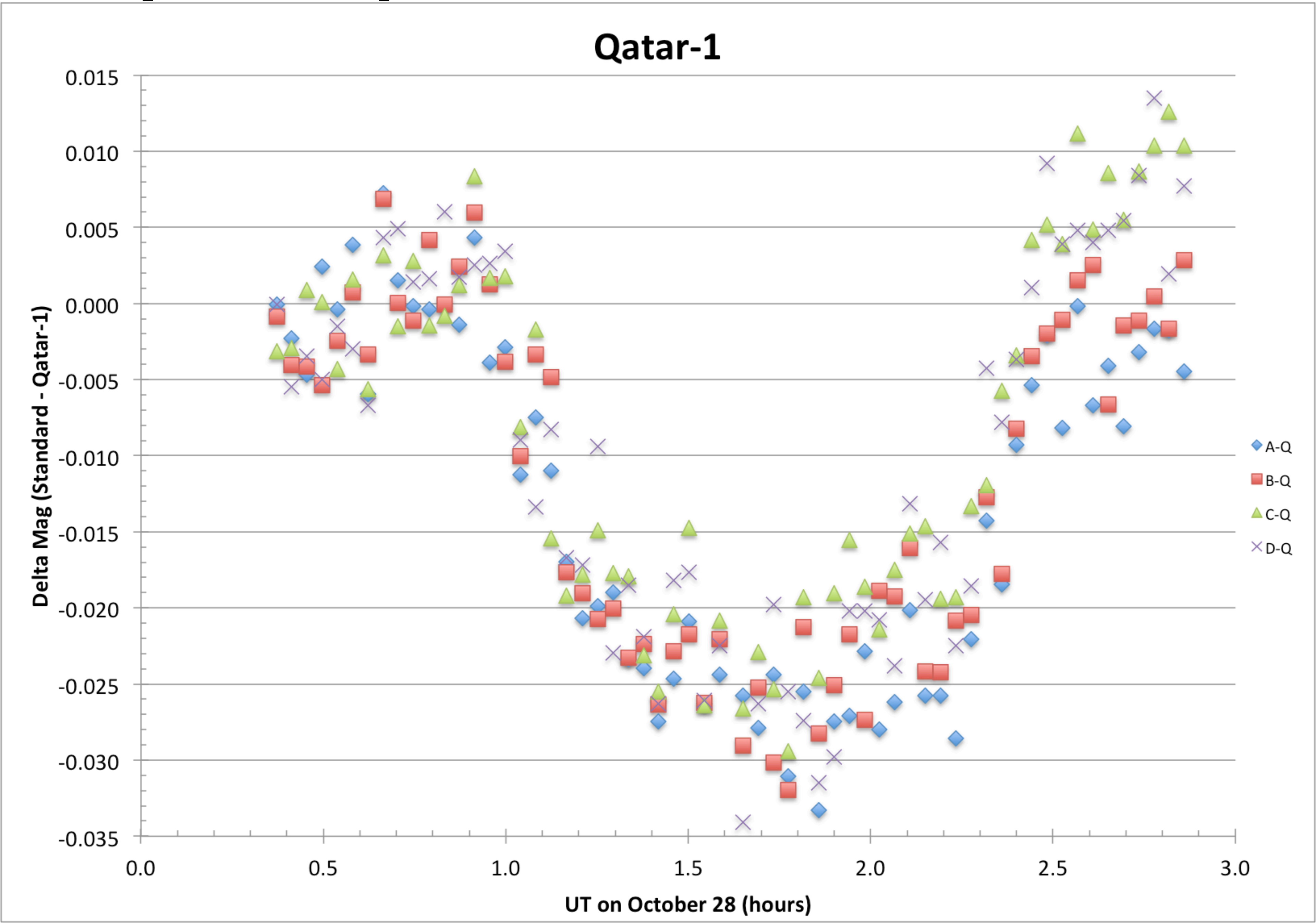
10
10.5
11
11.5
12
12.5
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Instrumental Magnitude
UT on Nov 01 (hours)
WASP 48
A (3925:146)
SUM

WASP-48

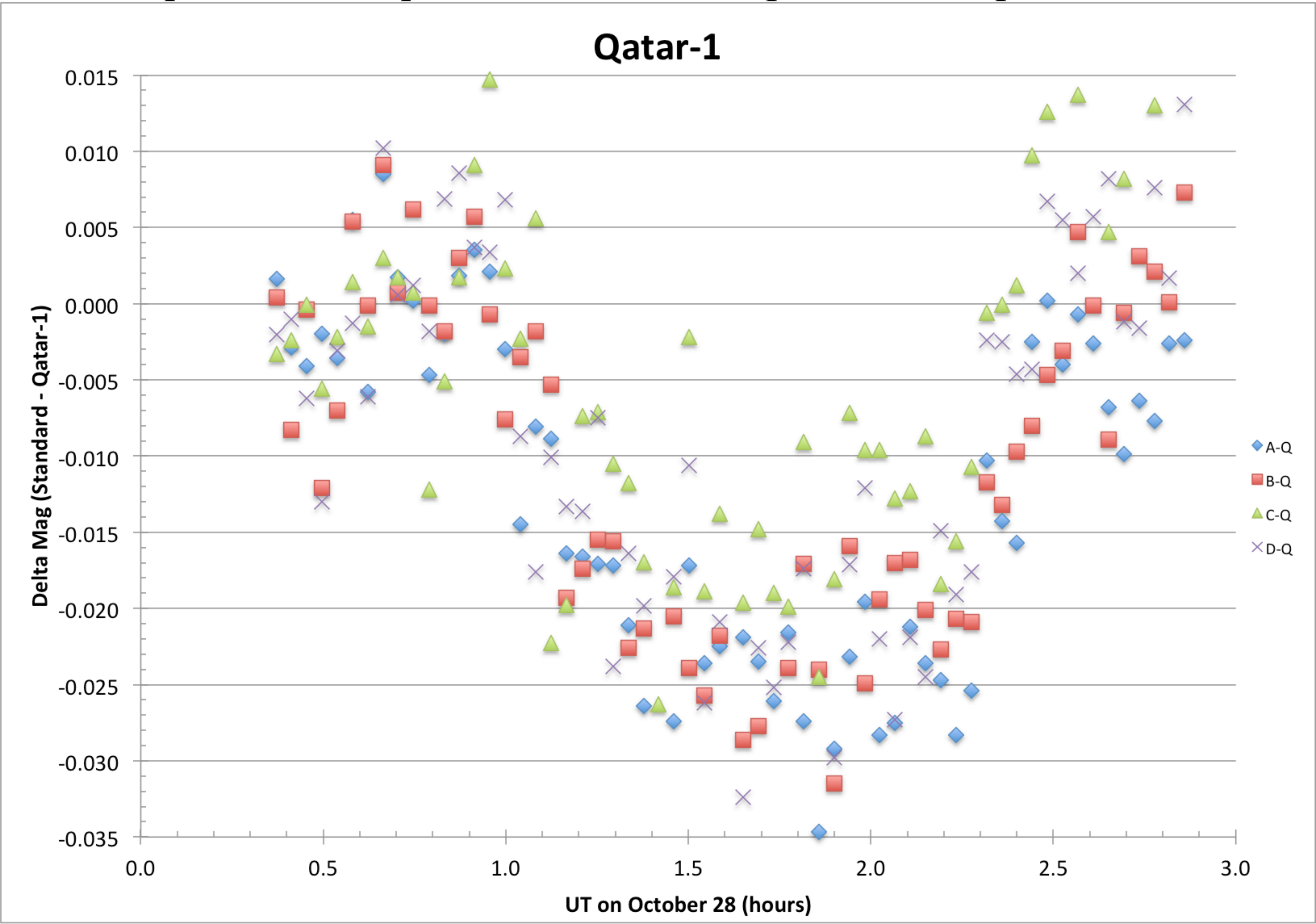


0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
Magnitude Difference
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
UT on Nov 01 (hours)
A - WASP-48
SUM- WASP-48

8 pixel radius aperture



12 pixel radius aperture; trends with position still present



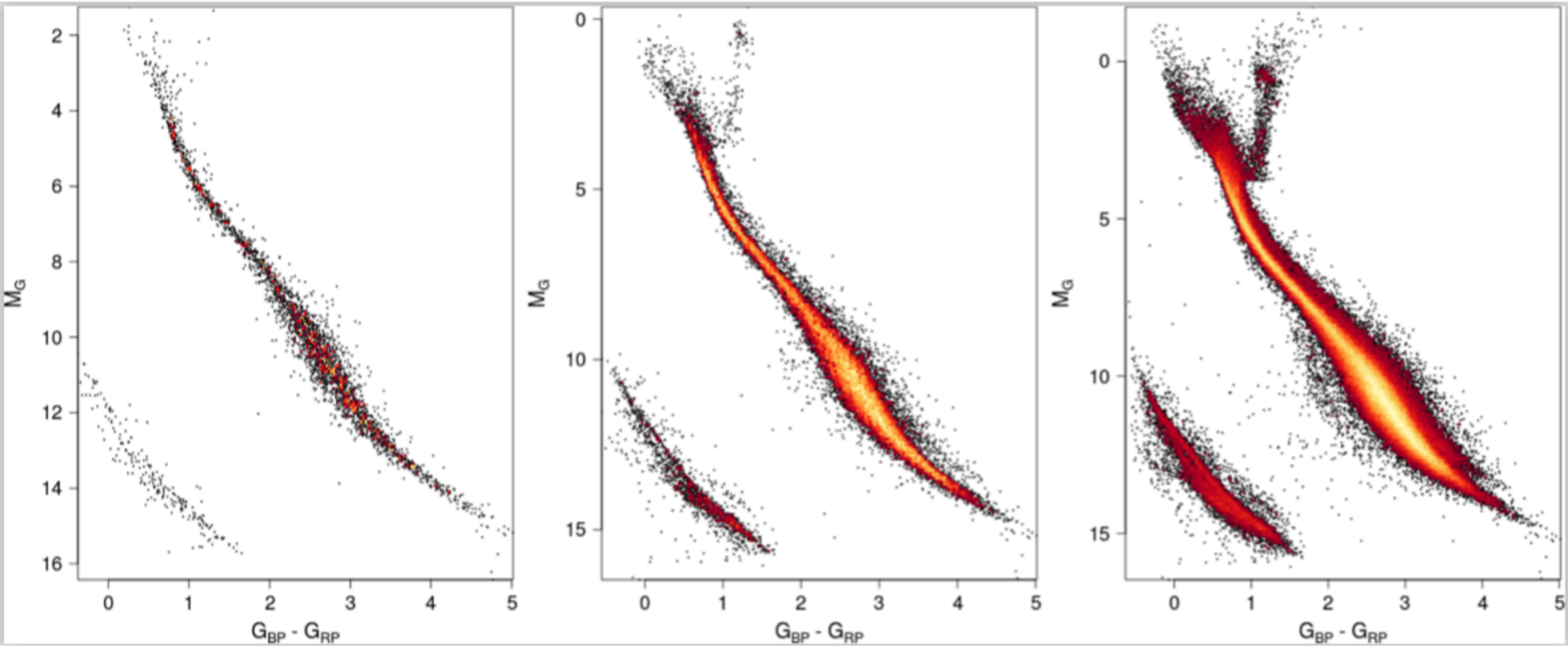
Stellar Photometry in Images

- Steps
  - Correction of image to a uniform, linear response.
    - Use the calibration menu item in *ruphast* to calibrate images one at a time.
  - Identify and determine positions of stars.
  - Measure the brightness of each star.

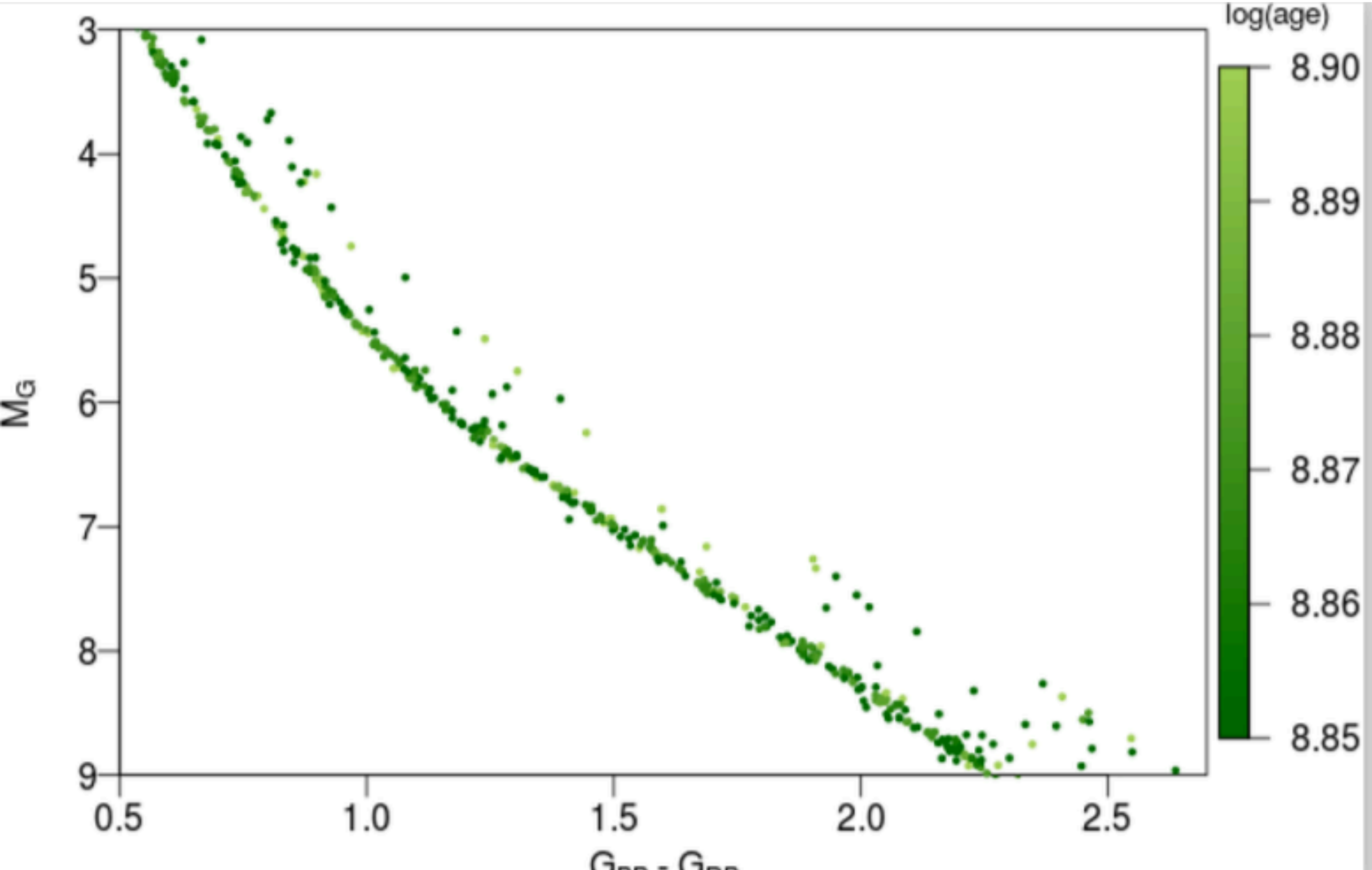
Color-Magnitude Diagram of an Open Cluster

- Plot stellar color versus brightness for stars in a cluster (a gravitationally bound group of stars that formed at the same time and are at the same distance).
- Determine cluster properties
  - Distance
  - Age
  - Open star cluster (and globular star clusters) have been our principal tools to understand stellar structure and evolution.

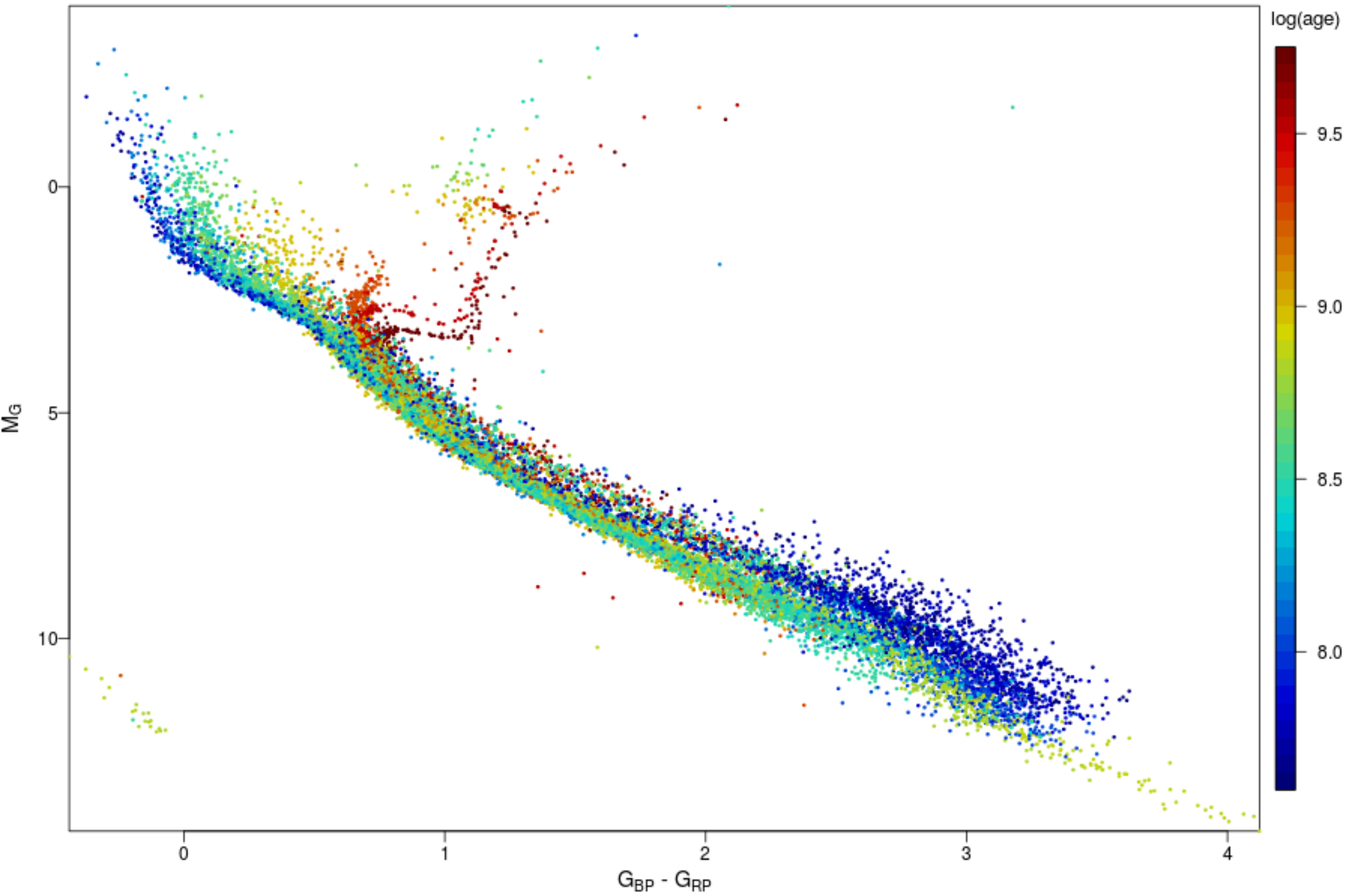
Gaia data release 2. Stars within 25 pc, 50 pc, and 100 pc of the Sun.

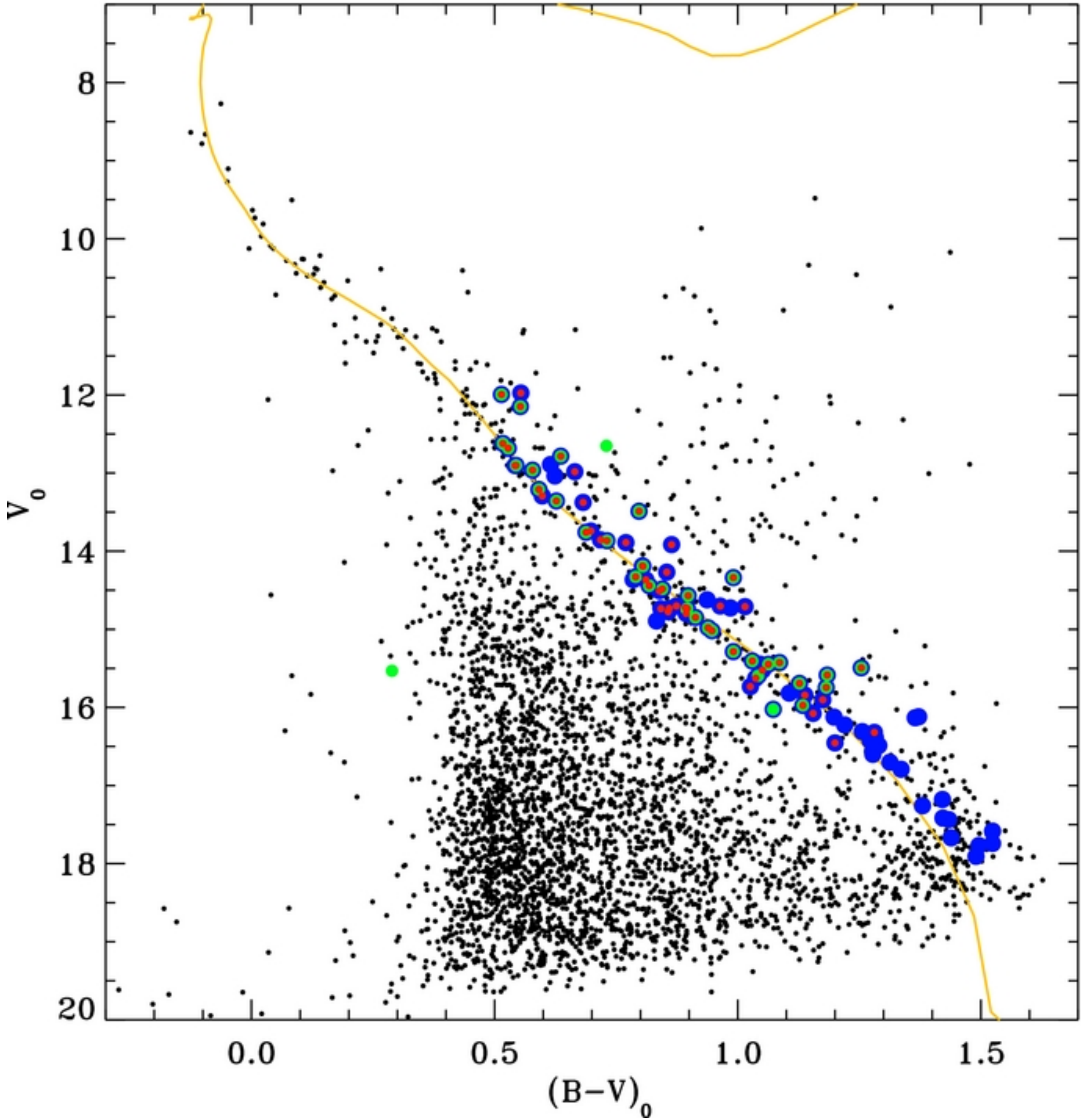


Gaia data release 2. Stars in the Hyades and Praesepe clusters.



Gaia data release 2. CMD for 32 open clusters.



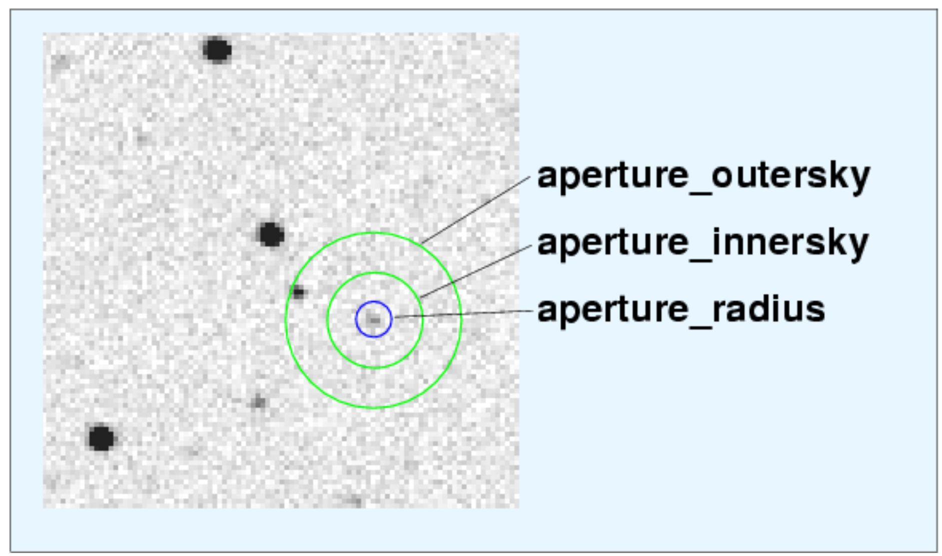


M34 CMD
WIYN 0.9m telescope
Green – proper motion member
Red – radial velocity member
Blue – photometric member

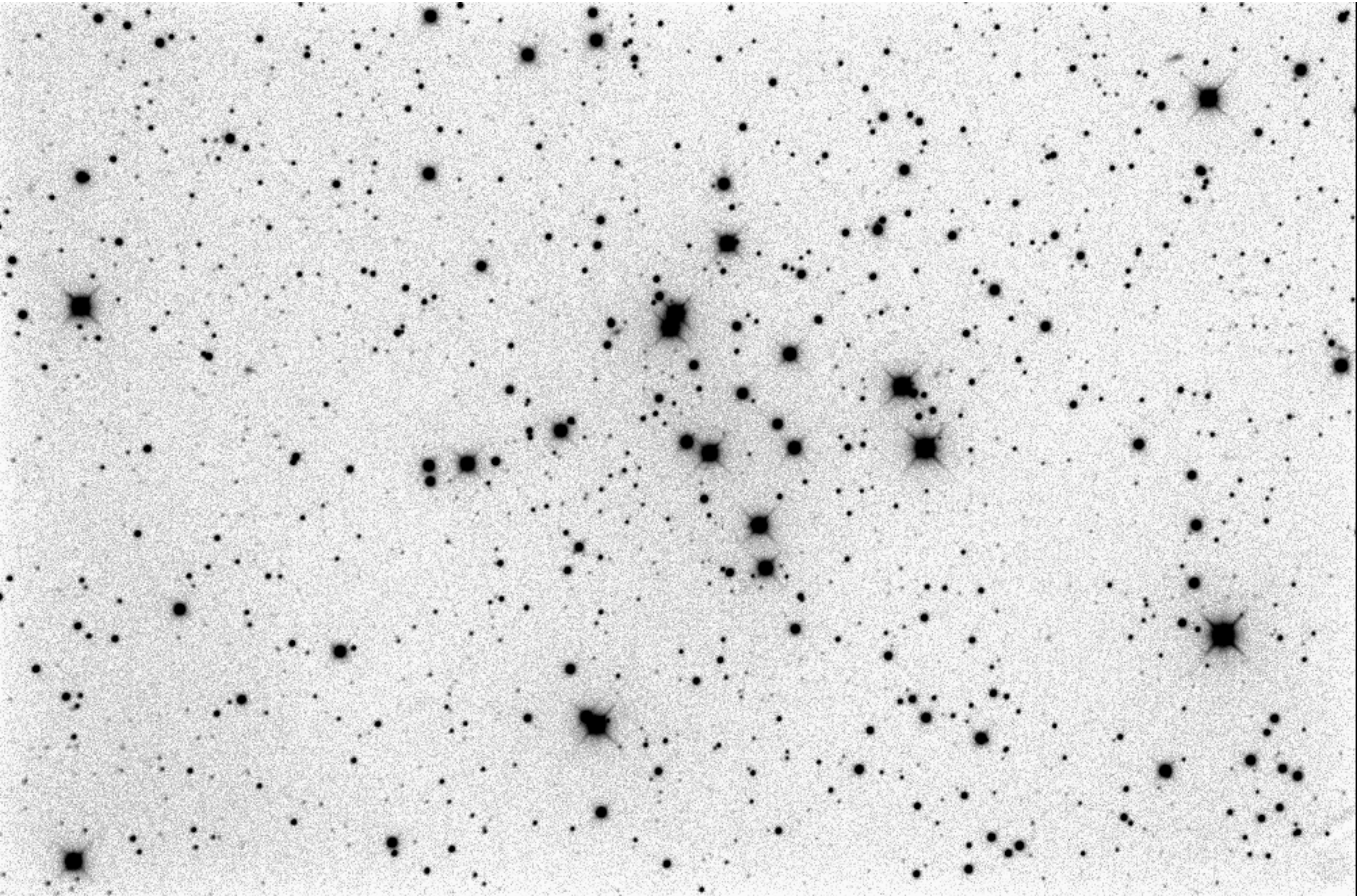
Meibom et al. 2011, ApJ, 733, 115

Measuring Stellar Brightness

- One Method: Aperture Photometry
  - Add up signal in pixels within a circular aperture centered on the star.
  - Subtract the contribution from the sky, estimated from pixels in a surrounding annulus.
    - Need a “robust” average sky value that removes the effect of any stars present.
  - (Relatively) simple.
  - How big to make the aperture?

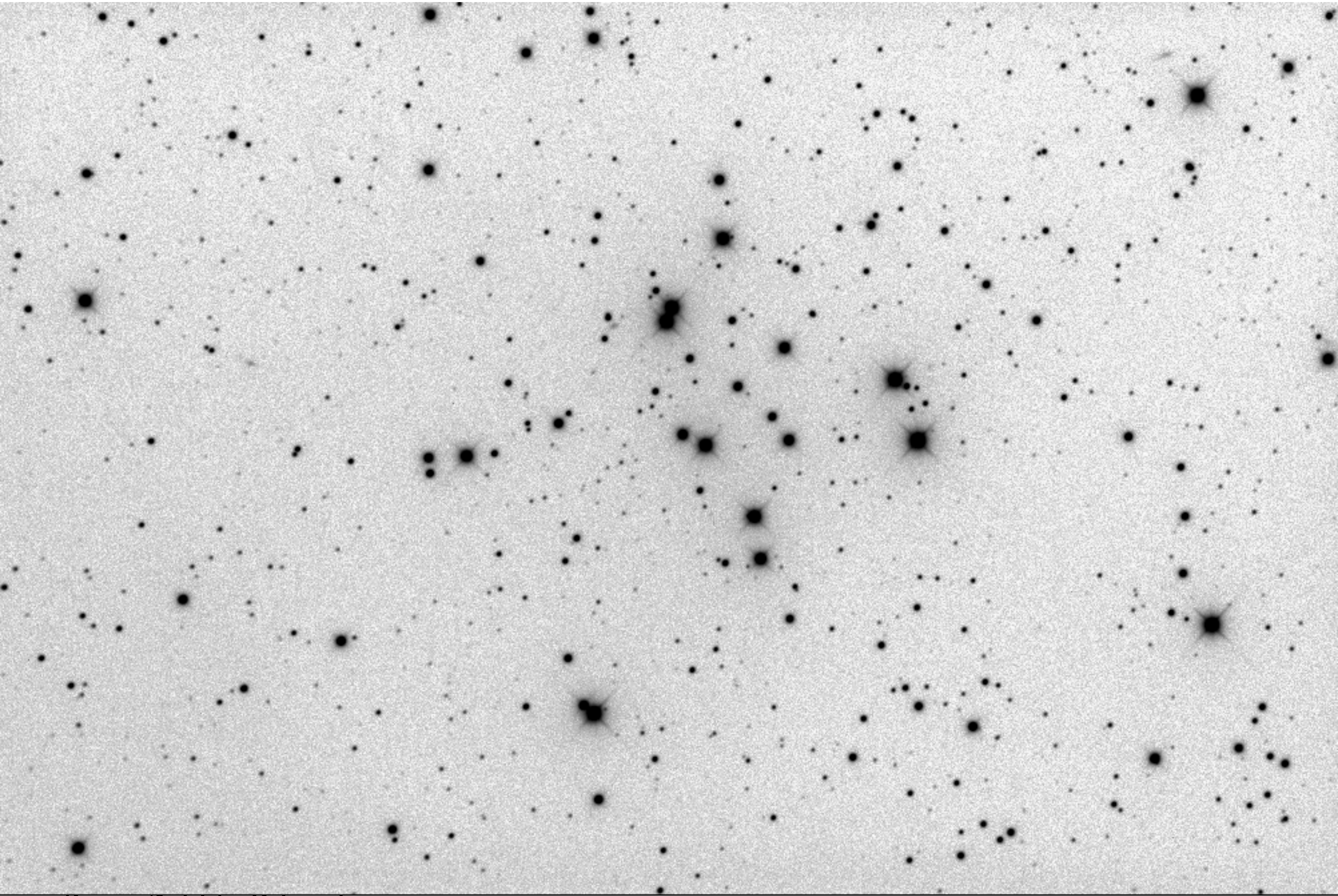


M34 V 300 sec



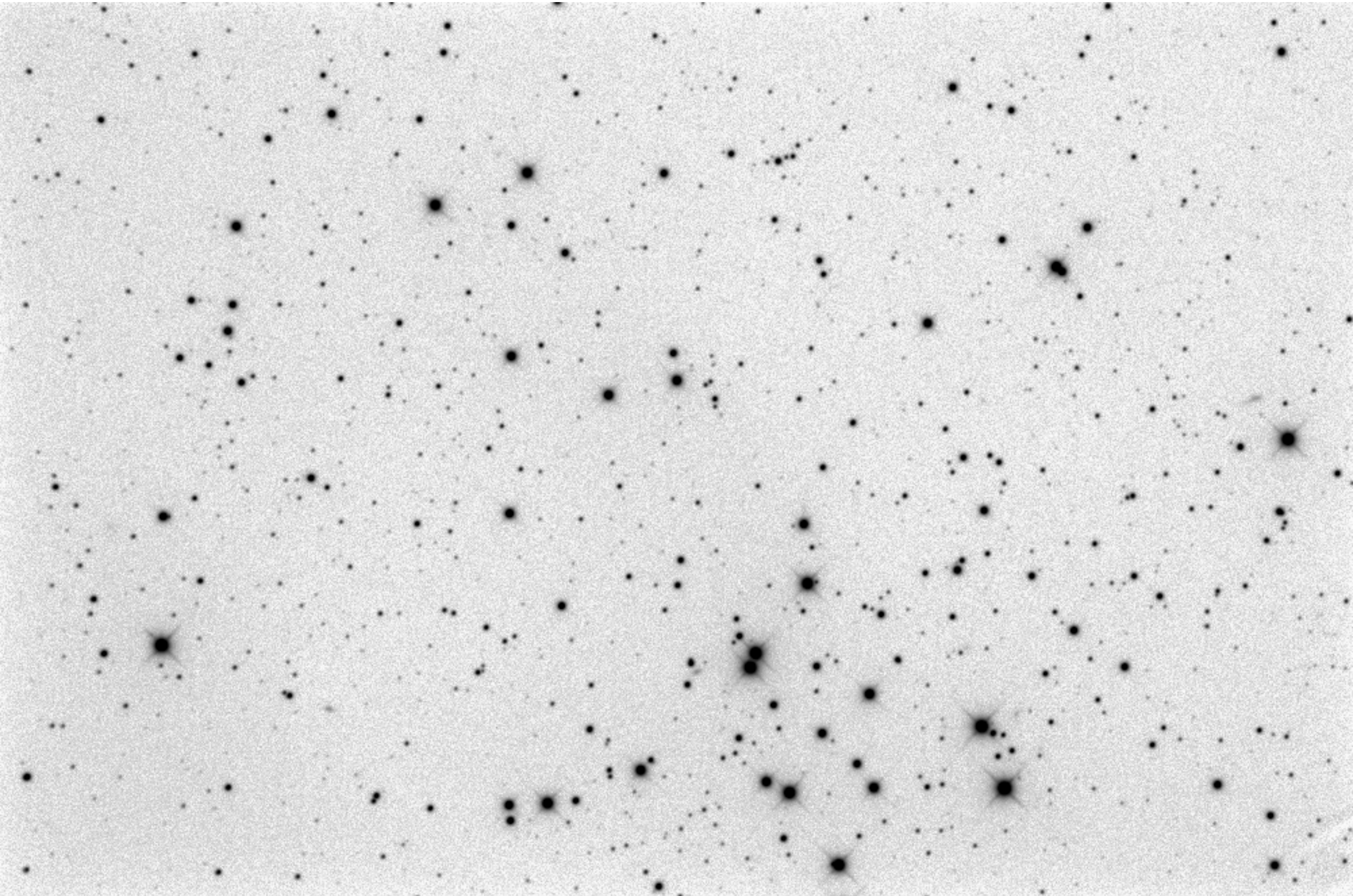
One field approximately centered on M34.

M34 B 300 sec



Same field in B band.

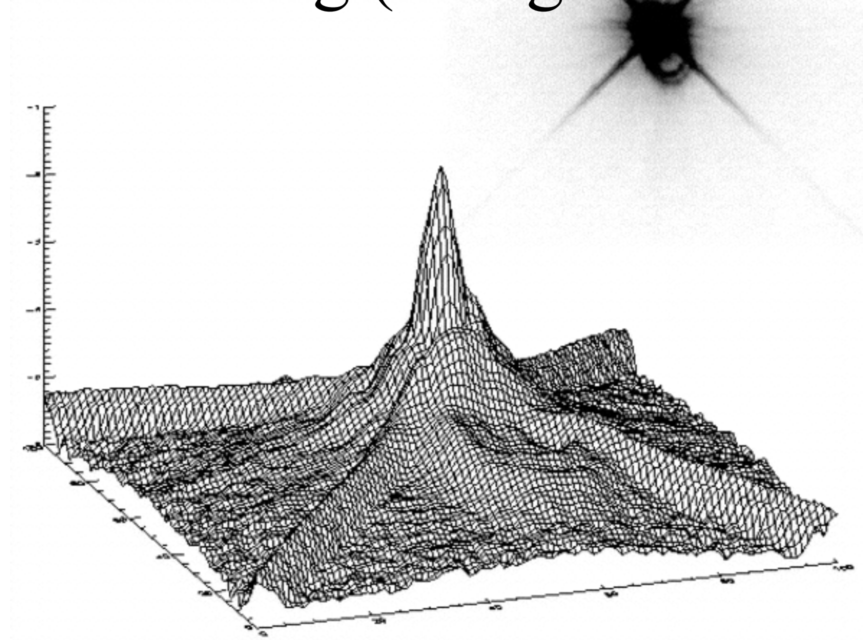
M34a V 300 sec (field with center offset)



Aperture photometry is tedious if there are many stars and fails if stars overlap.

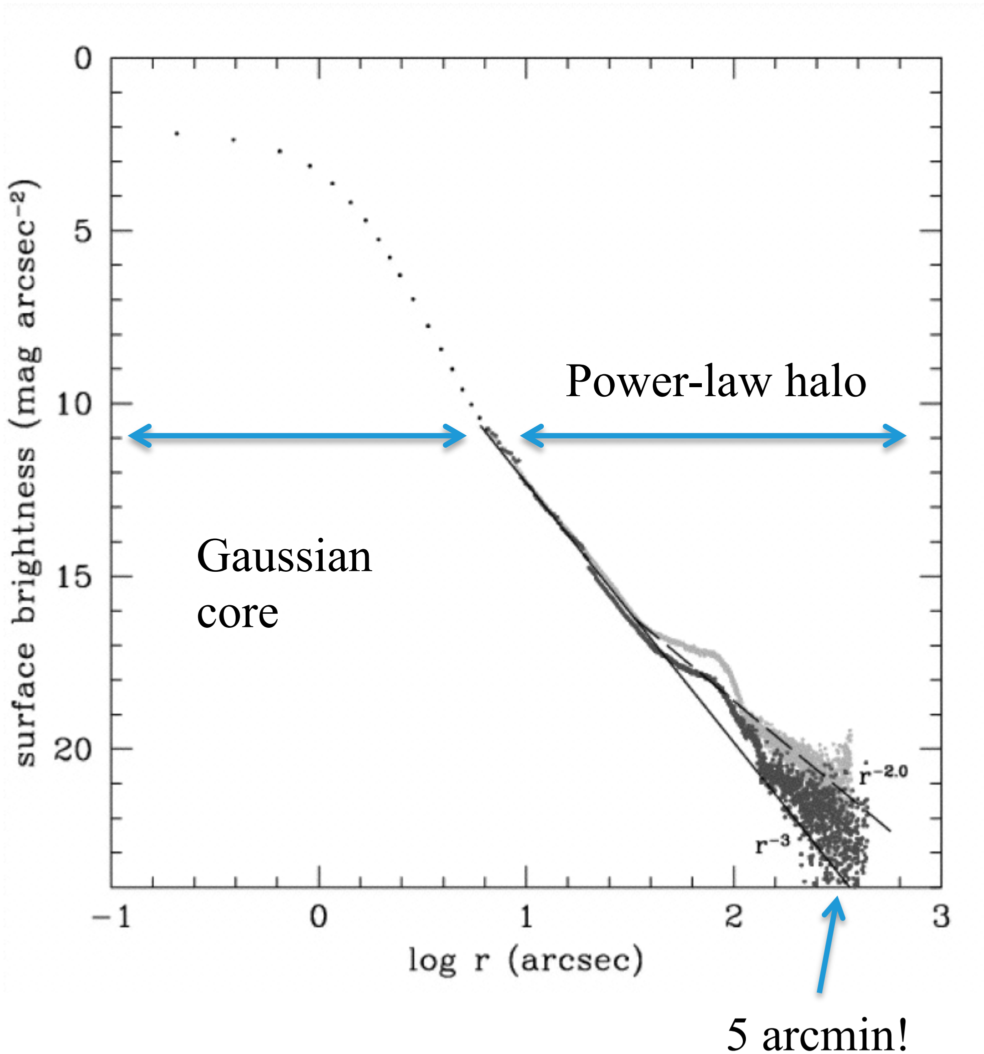
Measuring Stellar Brightness

- Another method of measuring stellar brightness uses the shape of a stellar image – the PSF
  - For space telescopes (such as HST), the core (and spikes) are mostly determined by diffraction due to the telescope aperture. This is less variable with time than seeing (though still affected by focus changes).



Stellar "point spread function" (PSF) for the Space Telescope Imaging Spectrograph (O'Dowd & Urry 2005)

- Shape of a stellar image – the "point spread function" (PSF)

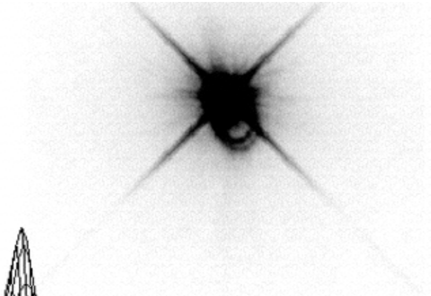


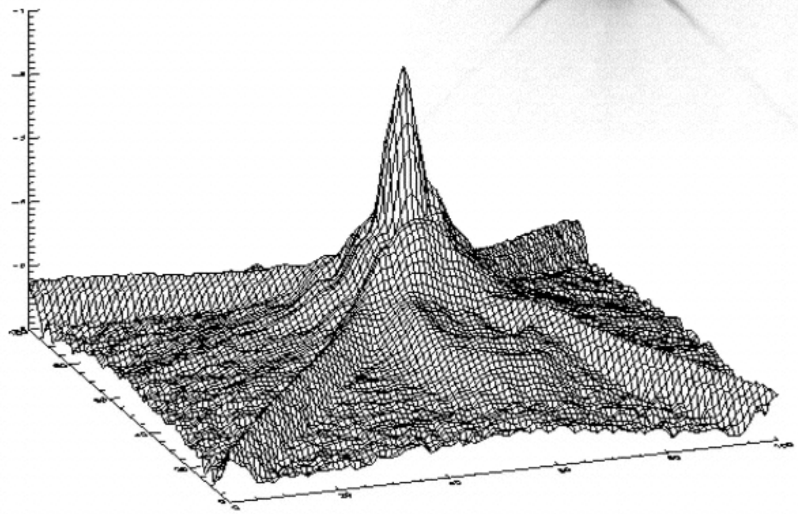
The core is caused by a) the bending of light in the rapidly changing inhomogeneous atmosphere – seeing and b) quality of the optical system (how well it is focused, …). It often varies over a night and within an image.

The origin of the halo is less well understood, but it is probably caused by diffraction from the telescope aperture and scattered light from dust and "micro-ripple" imperfections on surfaces of mirrors, filters, and other optical elements. The halo is constant at least over the several nights of an observing run.

Measuring Stellar Brightness

- PSF-fitting method:
  - Fit a functional form for the PSF plus a constant sky to the pixel values. Volume under the function is a measure of the stellar brightness.
  - Bright pixels in the core have the highest weight in the fit ➔ better S/N.
  - Can measure overlapping stars by simultaneously fitting two PSFs.
  - But greater complexity and higher computational cost.





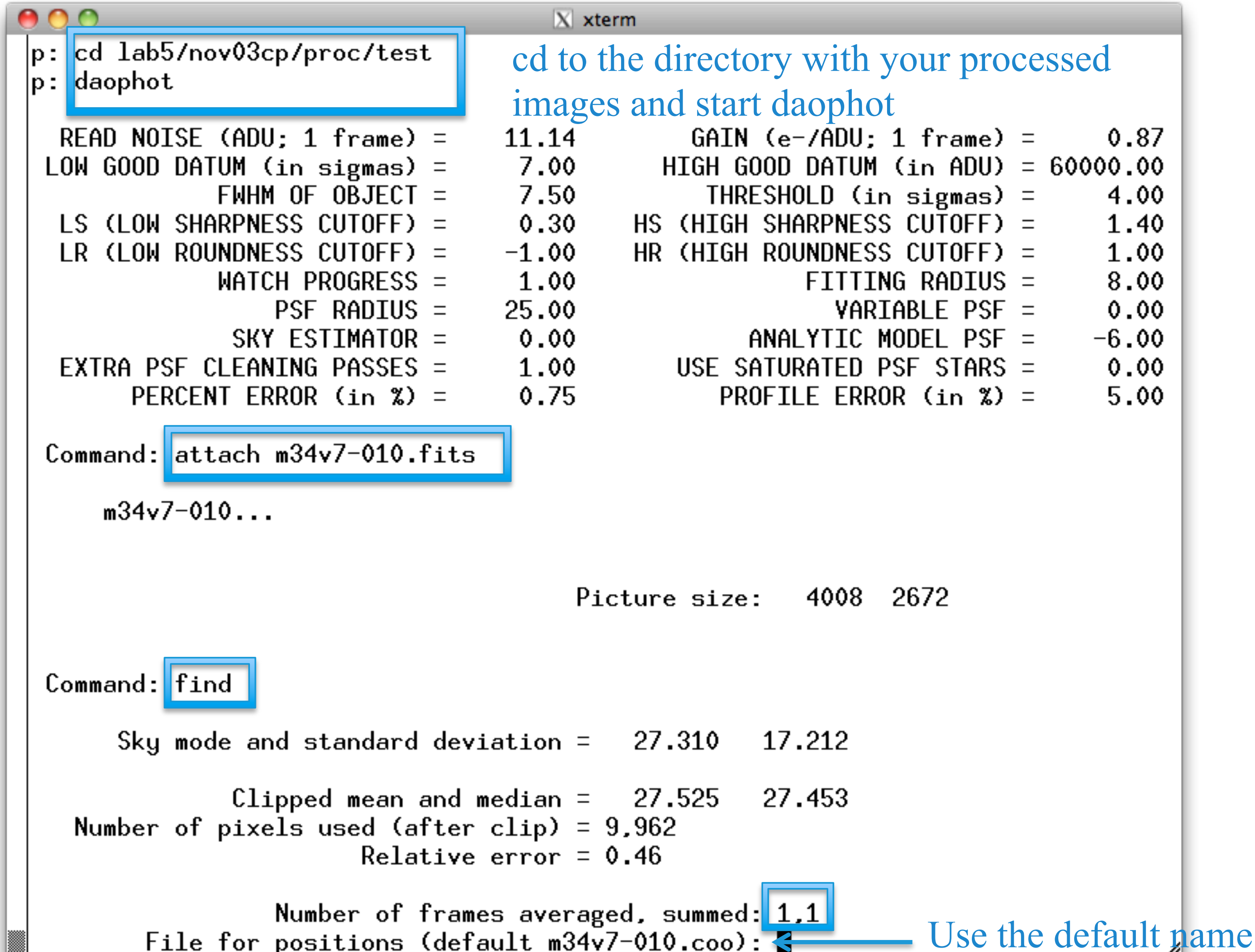
Stellar Photometry in Images

- Steps
  - Correction of image to a uniform, linear response.
  - Identify and determine positions of stars.
  - Measure the brightness of each star.
    - Do the above two steps with the DAOPHOT software package, which searches for stars in an image and measures their location and brightness.
    - Will measure each image separately since combining images is complex when some clouds are present.

DAOPHOT/ALLSTAR Package

- Finds stars in images and does both aperture and psf-fitting photometry.
- Run in a Unix/Linux terminal window.
- Command line driven programs (i.e., you type in commands), so are less intuitive to use.
- Start-up files initialize parameters.
  - daophot.opt: sets the gain, read noise, and typical FWHM of stars (plus other more esoteric things)
  - photo.opt: sets the aperture and sky annulus radii
  - allstar.opt: sets some parameters for the psf-fitting photometry

DAOPHOT – the *attach* command specifies the image to measure



DAOPHOT – the *find* command finds the stars in the image

ID # X Y Mag shape parameters

xterm

```
4952 3198.0 2672.0   -0.3  -10.00  -10.00
4953 3270.0 2672.0    0.0  -10.00  -10.00
4954 3298.0 2672.0   -0.2  -10.00  -10.00
4955 3423.0 2672.0   -0.3  -10.00  -10.00
4956 3559.0 2672.0   -0.2  -10.00  -10.00
4957 3575.0 2672.0   -0.4  -10.00  -10.00
4958 3693.0 2672.0   -0.2  -10.00  -10.00
4959 3761.0 2672.0   -0.2  -10.00  -10.00
4960 3778.0 2672.0    0.0  -10.00  -10.00
4961 3789.0 2672.0   -0.3  -10.00  -10.00
4962 3819.0 2672.0   -0.2  -10.00  -10.00
4963 3933.0 2672.0   -0.3  -10.00  -10.00

                     Are you happy with this? y

Command: phot

    File with aperture radii (default photo.opt):

 A1   RADIUS OF APERTURE  1 =     8.00     A2   RADIUS OF APERTURE  2 =     0.00
 A3   RADIUS OF APERTURE  3 =     0.00     A4   RADIUS OF APERTURE  4 =     0.00
 A5   RADIUS OF APERTURE  5 =     0.00     A6   RADIUS OF APERTURE  6 =     0.00
 A7   RADIUS OF APERTURE  7 =     0.00     A8   RADIUS OF APERTURE  8 =     0.00
 A9   RADIUS OF APERTURE  9 =     0.00     AA   RADIUS OF APERTURE 10 =     0.00
 AB   RADIUS OF APERTURE 11 =     0.00     AC   RADIUS OF APERTURE 12 =     0.00
 IS        INNER SKY RADIUS =    50.00     OS        OUTER SKY RADIUS =    60.00

PHO>

     Input position file (default m34v7-010.coo):
          Output file (default m34v7-010.ap):
```

Many stars found, some of which will turn out to be noise.

Are given the option to alter the radii here, but you do not need to.

Use default names

DAOPHOT – the *phot* command performs aperture photometry

ID # X Y Ap Mag unc sky level

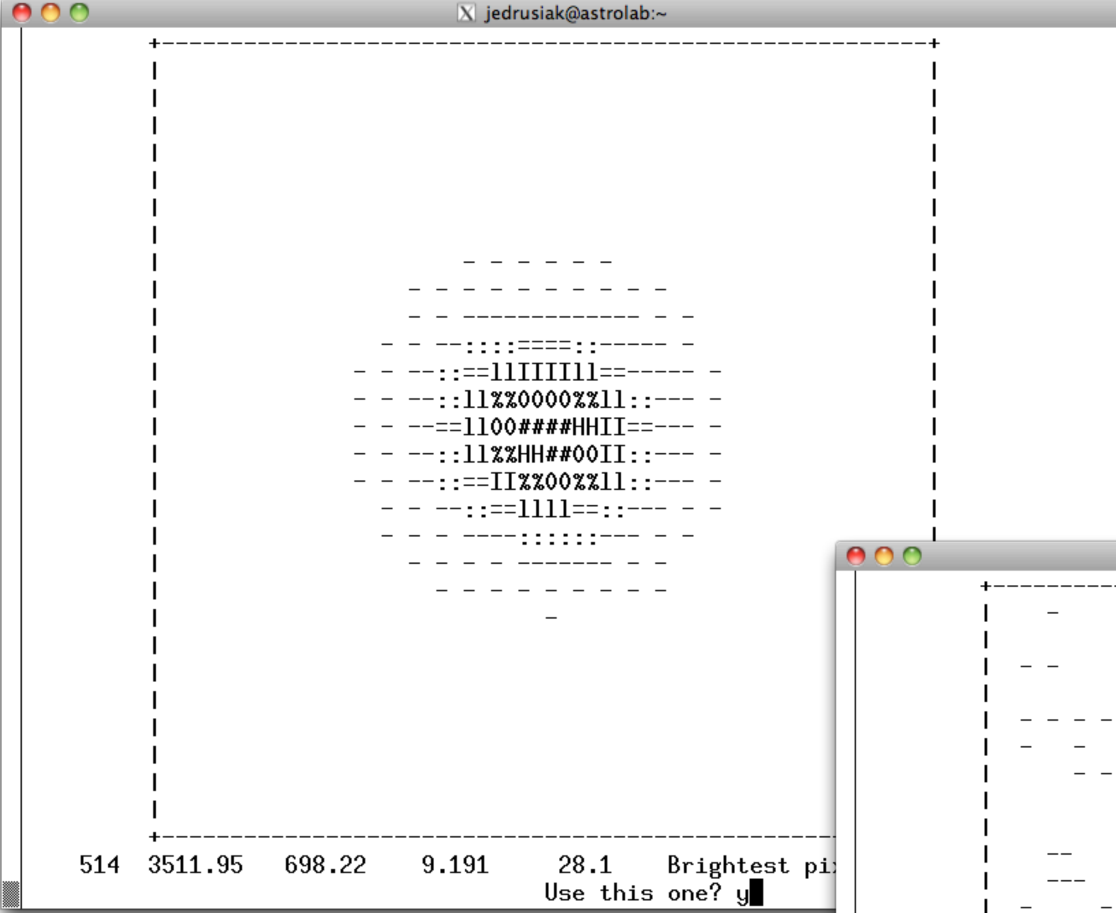
```
xterm
4942 2635.00 2672.00   97.999 +- 9.999    27.2
4943 2742.00 2672.00   97.999 +- 9.999    27.6
4944 2758.00 2672.00   97.999 +- 9.999    28.5
4945 2802.00 2672.00   97.999 +- 9.999    27.8
4946 2880.00 2672.00   97.999 +- 9.999    28.1
4947 2928.00 2672.00   97.999 +- 9.999    27.2
4948 2951.00 2672.00   97.999 +- 9.999    28.6
4949 3004.00 2672.00   97.999 +- 9.999    27.6
4950 3015.00 2672.00   97.999 +- 9.999    27.6
4951 3190.00 2672.00   97.999 +- 9.999    27.8
4952 3198.00 2672.00   97.999 +- 9.999    28.0
4953 3270.00 2672.00   97.999 +- 9.999    27.8
4954 3298.00 2672.00   97.999 +- 9.999    27.4
4955 3423.00 2672.00   97.999 +- 9.999    27.5
4956 3559.00 2672.00   97.999 +- 9.999    28.5
4957 3575.00 2672.00   97.999 +- 9.999    28.9
4958 3693.00 2672.00   97.999 +- 9.999    29.1
4959 3761.00 2672.00   97.999 +- 9.999    27.6
4960 3778.00 2672.00   97.999 +- 9.999    28.3
4961 3789.00 2672.00   97.999 +- 9.999    27.6
4962 3819.00 2672.00   97.999 +- 9.999    27.4
4963 3933.00 2672.00   97.999 +- 9.999    28.3

Estimated magnitude limit (Aperture 1): 16.9 +- 0.4 per star.


Command: pick

     Input file name (default m34v7-010.ap):
Desired number of stars, faintest magnitude: 30,99
     Output file name (default m34v7-010.lst):
```

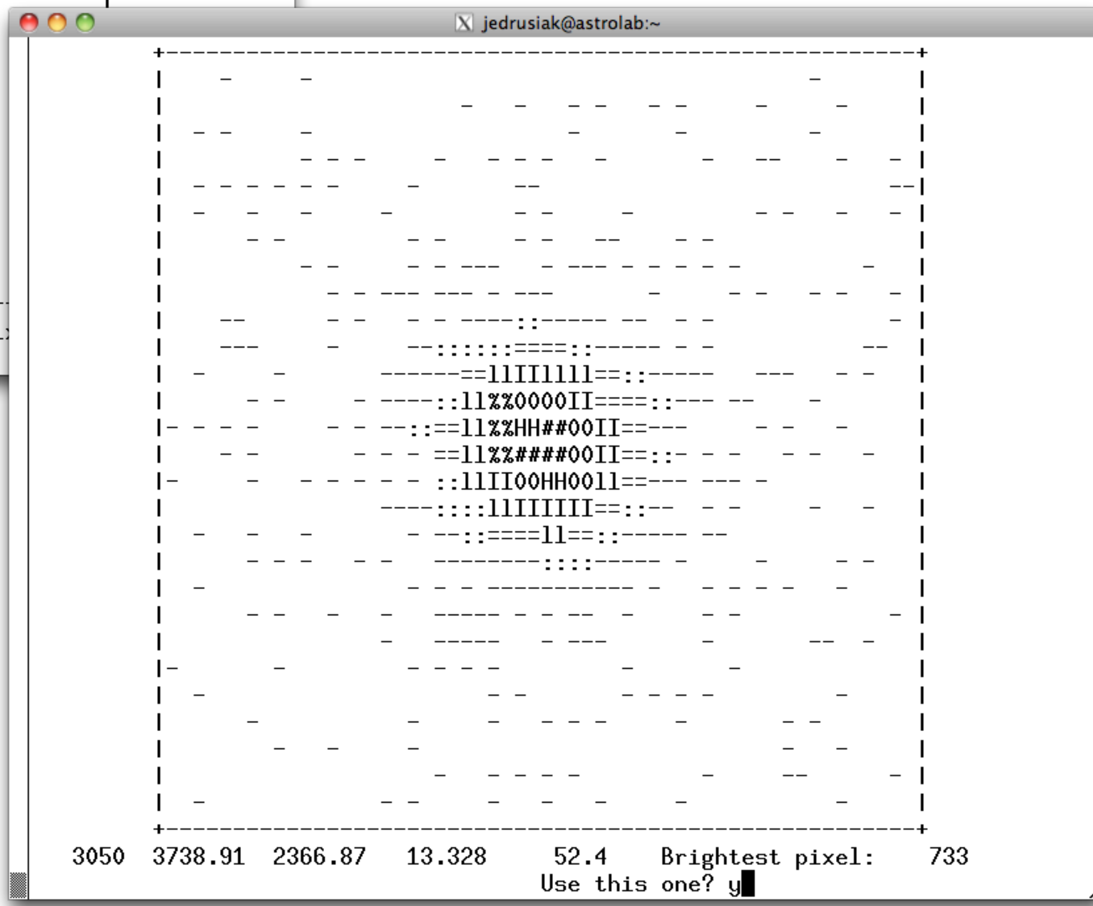
Pick 30 stars, regardless of magnitude.

DAOPHOT – *pick* chooses bright, unsaturated stars to determine the psf

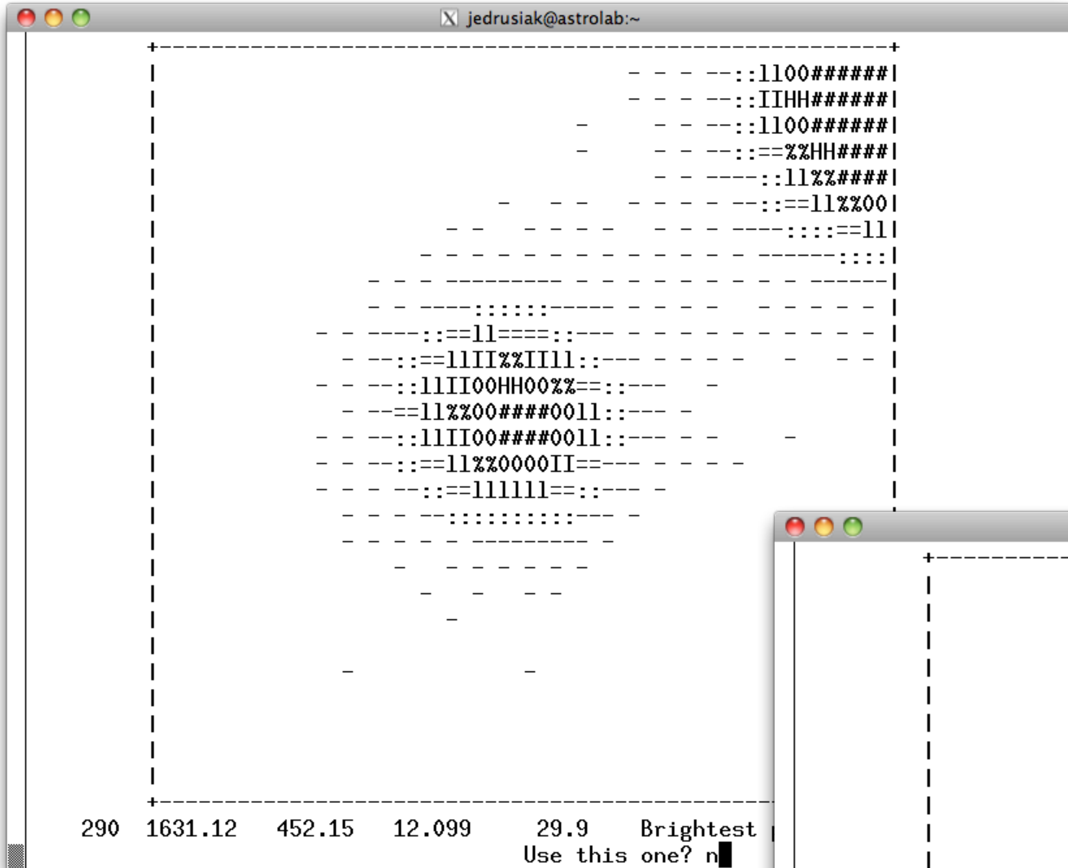
```
xterm
            4950 3015.00 2672.00   97.999 +- 9.999    27.6
            4951 3190.00 2672.00   97.999 +- 9.999    27.8
            4952 3198.00 2672.00   97.999 +- 9.999    28.0
            4953 3270.00 2672.00   97.999 +- 9.999    27.8
            4954 3298.00 2672.00   97.999 +- 9.999    27.4
            4955 3423.00 2672.00   97.999 +- 9.999    27.5
            4956 3559.00 2672.00   97.999 +- 9.999    28.5
            4957 3575.00 2672.00   97.999 +- 9.999    28.9
            4958 3693.00 2672.00   97.999 +- 9.999    29.1
            4959 3761.00 2672.00   97.999 +- 9.999    27.6
            4960 3778.00 2672.00   97.999 +- 9.999    28.3
            4961 3789.00 2672.00   97.999 +- 9.999    27.6
            4962 3819.00 2672.00   97.999 +- 9.999    27.4
            4963 3933.00 2672.00   97.999 +- 9.999    28.3

 Estimated magnitude limit (Aperture 1): 16.9 +- 0.4 per star.


Command: pick

           Input file name (default m34v7-010.ap):
      Desired number of stars, faintest magnitude: 30,99
         Output file name (default m34v7-010.lst):

       30 suitable candidates were found.


Command: psf

File with aperture results (default m34v7-010.ap):
      File with PSF stars (default m34v7-010.lst):
         File for the PSF (default m34v7-010.psf):
```

DAOPHOT – *psf* uses the picked stars to determine the psf. It shows a simple plot of each star and you decide whether to use it or not.

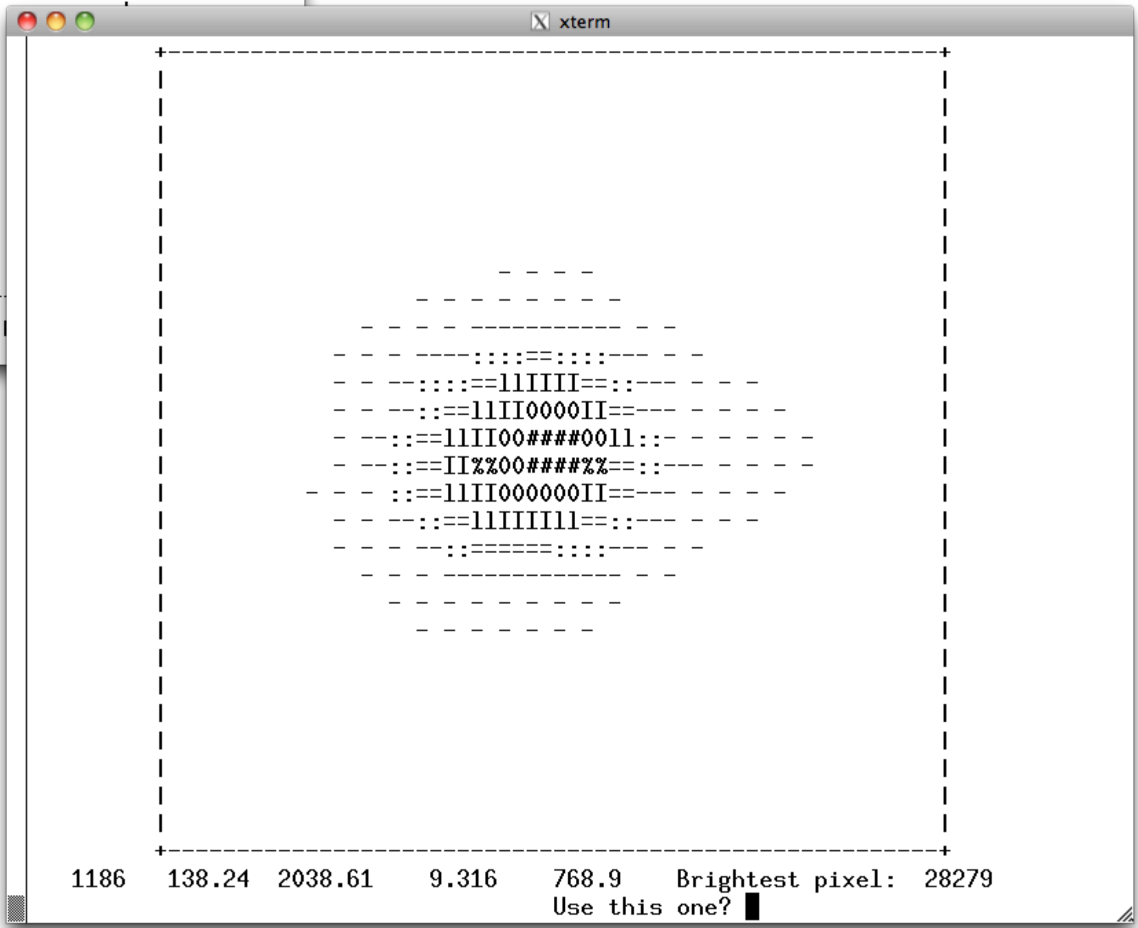




Want bright, isolated stars. These are OK.



These stars should not be used to determine the psf.



```
xterm
    236  2796.85    390.97    12.391      27.6     Brightest pixel:    1749
                                               Use this one? y


        Chi       Parameters...
>>    0.0475    4.00399    3.89406
>>    0.0665    2.54644    2.53558   -0.05137
>>    0.0413    3.54019    3.43217   -0.00949
>>    0.0411    3.66591    3.55743   -0.00837
>>    0.0615    3.28475    3.14228   -0.01441
>>    0.0410    3.62599    3.52361    0.64871   -0.01181


 Profile errors:

    514  0.021        1802  0.027        1054  0.042        3969  0.035         461  0.069
    267  0.046        1100  0.028        1588  0.030        3821  0.042        1044  0.049
   1426  0.025         840  0.029        1193  0.034        4237  0.049        4647  0.025
   1835  0.102 ?      2230  0.028        1538  0.025         179  0.041         236  0.035
   1728  0.027          23  0.135 *      1114  0.029        2665  0.034
   3410  0.027         695  0.029        1142  0.031        2735  0.049

   Computed          103    rows of          103    in the PSF.

 File with PSF stars and neighbors = m34v7-010.nei

 Command: exit


 Good bye.

p: 
```

Tries six different functional forms for the psf and chooses the one that fits best. Differences from the functional form are handled with a look-up table (so any psf shape can be accommodated).

DAOPHOT – *exit* returns to the Unix command line xterm

```
p: allstar

          FITTING RADIUS =     8.00        CE (CLIPPING EXPONENT) =     6.00
   REDETERMINE CENTROIDS =     1.00          CR (CLIPPING RANGE) =     2.50
          WATCH PROGRESS =     1.00           MAXIMUM GROUP SIZE =    50.00
    PERCENT ERROR (in %) =     0.75         PROFILE ERROR (in %) =     5.00
   IS (INNER SKY RADIUS) =    35.00        OS (OUTER SKY RADIUS) =    50.00

 OPT>
```

(are given the option to change parameters here, but this is unnecessary)

```
                                     Input image name: m34v7-010.fits

     m34v7-010...

                                          Picture size:    4008   2672

           File with the PSF (default m34v7-010.psf):
                   Input file (default m34v7-010.ap):
            File for results (default m34v7-010.als):
    Name for subtracted image (default m34v7-010s):

    4963 stars.  <<

 I = iteration number

 R = number of stars that remain

 D = number of stars that disappeared
```

Use the default input and output filenames.

ALLSTAR – does the psf-fitting photometry xterm

```
I = iteration number

R = number of stars that remain

D = number of stars that disappeared

C = number of stars that converged



     I        R        D        C
     1     4963        0        0   <<
     2     4963        0        0   <<
     3     4963        0        0   <<
     4     4800       89       74   <<
     5     4203      194      566   <<
     6     3002      703     1258   <<
     7     2148     1436     1379   <<
     8     1508     1820     1635   <<
     9     1179     2111     1673   <<
    10      946     2319     1698   <<
    11      702     2537     1724   <<
    12      477     2744     1742   <<
    13      292     2915     1756   <<
    14      131     3063     1769   <<
    15       46     3139     1778   <<
    16       39     3139     1785   <<
    17       29     3139     1795   <<
    18       24     3139     1800   <<
    19       14     3139     1810   <<
    20       14     3139     1810   <<
    21       12     3139     1812   <<
```

ALLSTAR fits all of the stars in the image simultaneously, so overlapping stars are handled correctly (assuming that both stars are in the input list). The solution is done iteratively.

Original 7-second, V-band image

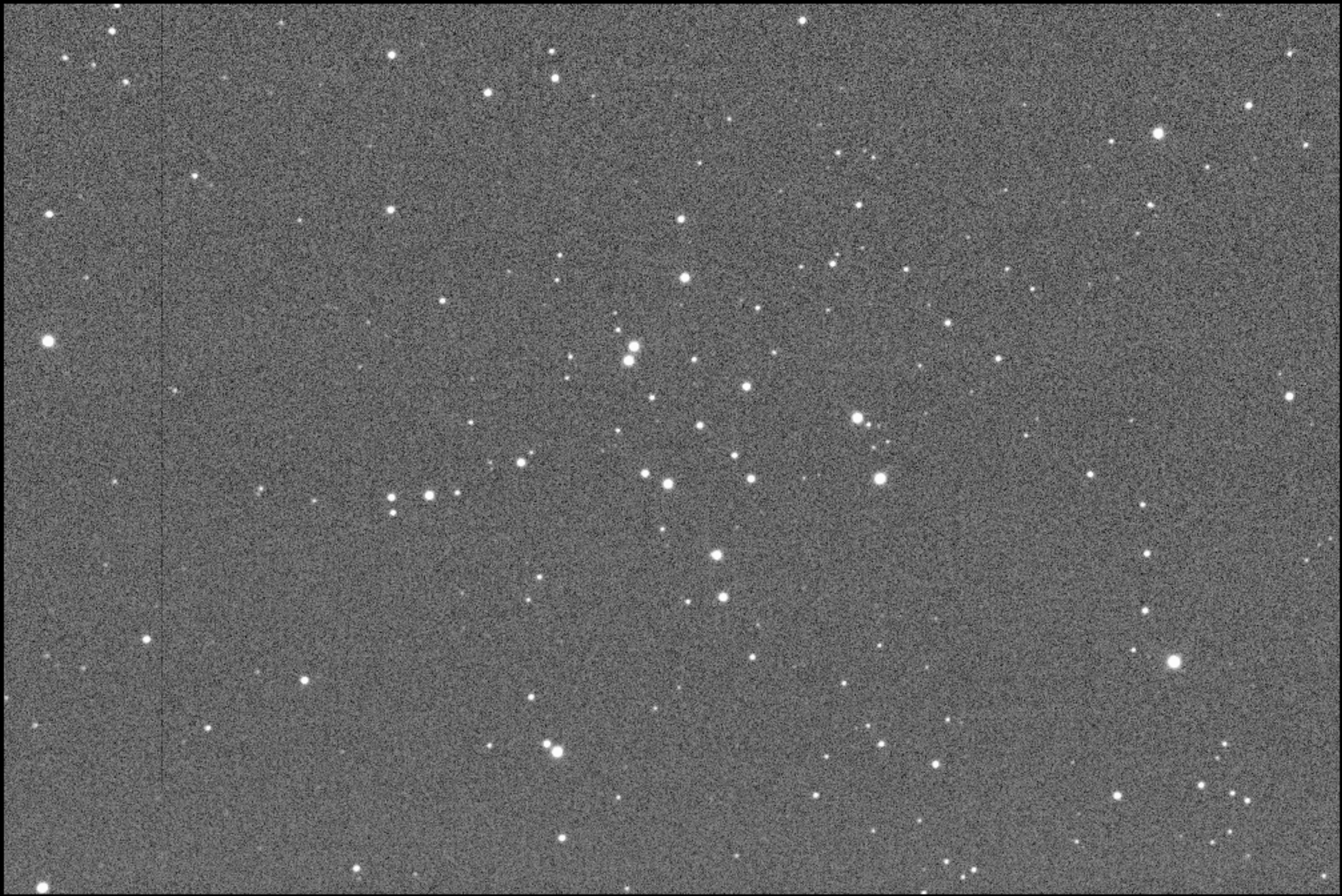
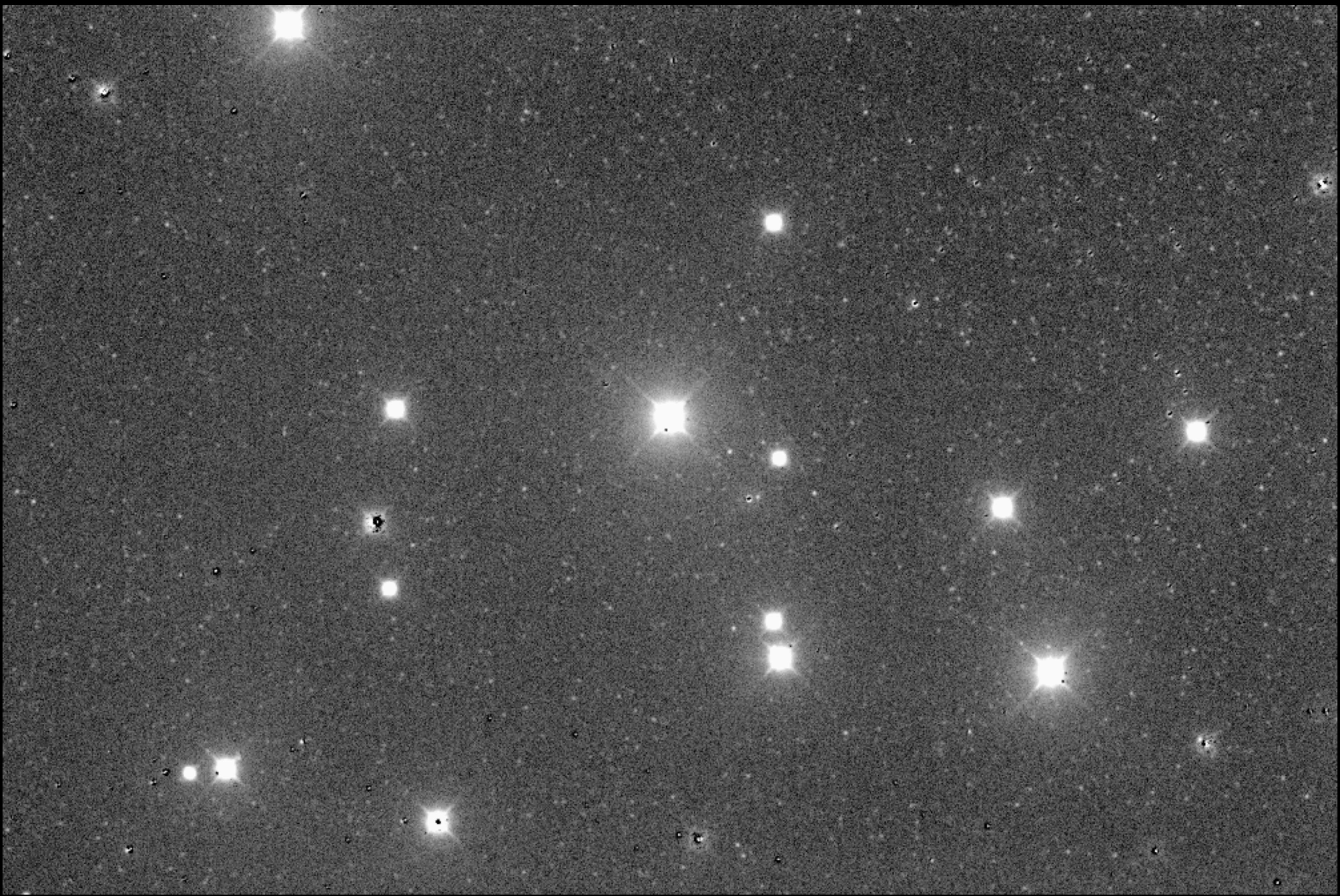


Image with the fitted psf's subtracted

Long exposure, V-band image

Fitted psf's subtracted. Note saturated stars are not fitted.



```
jedrusiak@astrolab:~
-rw-r--r--  1 pryor  staff  106946 Nov  8 17:23 m34v7-043.als
p: daomatch

                    Master input file: m34v7-010.als
      Output file name (default m34v7-010.mch):
                      Next input file: m34v7-042.als


           Frame 2:
      star   1  2  3
           +---------
 Frame 1: 1 |  1  -  -
          2 |  -  1  -
          3 |  -  -  1



 m34v7-042.als                   -2     1   1.000   0.000   0.000   1.000   0.
03

        3    0.994    0.000    0.000    0.003    0.002
        2    2.000    2.000    0.400    0.500
 WT  0.9942961       <      2.000000


           Frame 2:
      star   1  2  3  4
           +------------
 Frame 1: 1 |  3  -  -  -
          2 |  -  3  -  -
          3 |  -  -  3  -
          4 |  -  -  -  3



 m34v7-042.als                   -2     1   1.000   0.000   0.000   1.000   C
```

daomatch begins the process of matching stars in the ALLSTAR output files for each image

```
jedrusiak@astrolab:~

 m34v180-049.als                    0     3   1.000   0.000   0.000   1.000   3.
60


       12    1.985    0.000    0.000    0.016    0.005
        5    2.000    2.000    0.400    0.500
 WT   1.984952        <      2.000000


              Frame 2:
       star   1  2  3  4  5  6
             +----------------
 Frame 1: 1  |  6  -  -  -  -  -
          2  |  -  6  -  -  -  -
          3  |  -  -  6  -  -  -
          4  |  -  -  -  -  -  6
          5  |  -  -  -  -  6  -
          6  |  -  -  -  -  -  -



 m34v180-049.als                    0     3   1.000   0.000   0.000   1.000   3.
53


       30    6.941    0.000    0.000    0.021    0.005
       11    2.000    2.000    0.400    0.500
         45  >          6



                   Next input file (default EXIT):


 Good bye.

p: 
```

Keep entering files until have done all of them for a given filter (V or B) *daomaster* finishes the job of matching the stars in the "als" files.

jedrusiak@astrolab:~

```
p: daomaster

     MONGO version


                      File with list of input files: m34v7-010.mch

 9 input files

Maximum permitted number of stars in the master list: 500,000

  Minimum number, minimum fraction, enough frames: 3,0.33,3
                                    Maximum sigma: 10.

              Desired degrees of freedom ---

                 2:  Translations only
                 4:  Translations, rotation, and scale
                 6:  Six-constant linear transformation
                12:  Quadratic transformation
                20:  Cubic transformation

                                      Your choice: 6
                           Critical match-up radius: 3.0


 0.55 0.47     -2      1  1.000  0.000  0.000  1.000   0.03 0.017   236  2 m34v7-042.als
 0.57 0.50     -2      1  1.000  0.000  0.000  1.000  -0.86 0.026   156  2 m34v7-043.als
 0.54 0.45      0      3  1.000  0.000  0.000  1.000   1.30 0.029   252  2 m34v35-044.als
 0.54 0.51     -1      2  1.000  0.000  0.000  1.000   1.36 0.027   272  2 m34v35-045.als
 0.55 0.51     -1      3  1.000  0.000  0.000  1.000   1.53 0.032   281  2 m34v35-046.als
 0.60 0.54      1      2  1.000  0.000  0.000  1.000   3.42 0.046   288  2 m34v180-047.als
```

Keep stars that appear in three or more images.

jedrusiak@astrolab:~

```
  0.54 0.45      0      3  1.000  0.000  0.000  1.000   1.30 0.029    252  2 m34v35-044.als
  0.54 0.51     -1      2  1.000  0.000  0.000  1.000   1.36 0.027    272  2 m34v35-045.als
  0.55 0.51     -1      3  1.000  0.000  0.000  1.000   1.53 0.032    281  2 m34v35-046.als
  0.60 0.54      1      2  1.000  0.000  0.000  1.000   3.42 0.046    288  2 m34v180-047.als
  0.60 0.59      0      2  1.000  0.000  0.000  1.000   3.56 0.047    290  2 m34v180-048.als
  0.61 0.57      0      3  1.000  0.000  0.000  1.000   3.56 0.050    289  2 m34v180-049.als

  811 stars within radius 3.000


                  New match-up radius (0 to exit): 0

      Transformations are in the sense  STANDARD = fn(OBSERVED).

                              Assign new star IDs? n

                           Now, do you want...
           A file with mean magnitudes and scatter? y
          Output file name (default m34v7-010.mag):
       A file with corrected magnitudes and errors? y
          Output file name (default m34v7-010.cor):
            A file with raw magnitudes and errors? n
              A file with the new transformations? n
                   A file with the transfer table? n
                           Individual .COO files? n
                        Simply transfer star IDs? n

 Good bye.

p: edit m34v7-010.mag
p: edit m34v7-010.cor
p:
```

M34 instrumental (v, b-v) color-magnitude diagram. 1,235 stars