# EMCCD Sensors as Slit Viewing and Guide Cameras

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EMCCD Spectroscopy Workshop

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# Application Requirements

- There are 2 different applications: Slit Viewing and Guider
- Slit Viewing Application
  - Requirements:
    - Quickly identify the target and place it on the DBSP entrance slit.
    - Ability to visualize very faint targets in the minimum amount of time.
    - Monitor the targets position while taking science observations
    - Required operational magnitude range from 1 to 20$^{th}$ magnitude objects
- Guider Application
  - Requirements
    - Quickly identify and move the guider head to selected guide star.
    - Ability to maintain telescopes position to < 0.5 arc seconds so that stars stay within the DBSP entrance slit while guiding.
    - Ability to guide on both bright and faint objects.

# Palomar Observatory Slit Viewing Cameras

- **Shepherd** slit viewing camera – **Xybion** TV camera using intensified interline CCD (756x581). 60Hz refresh rate. Preferred by telescope operators due to high refresh rate.
- **Finger Lakes Instruments** – Microline ML1001 1024x1024 CCD sensor. Minimum integration time 0.3 seconds, typical exposure time 1.0 seconds
  - Longer exposure times possible but makes target acquisition very slow.
- Limiting magnitude = 16$^{th}$ magnitude to 17$^{th}$ on dark nights with good seeing

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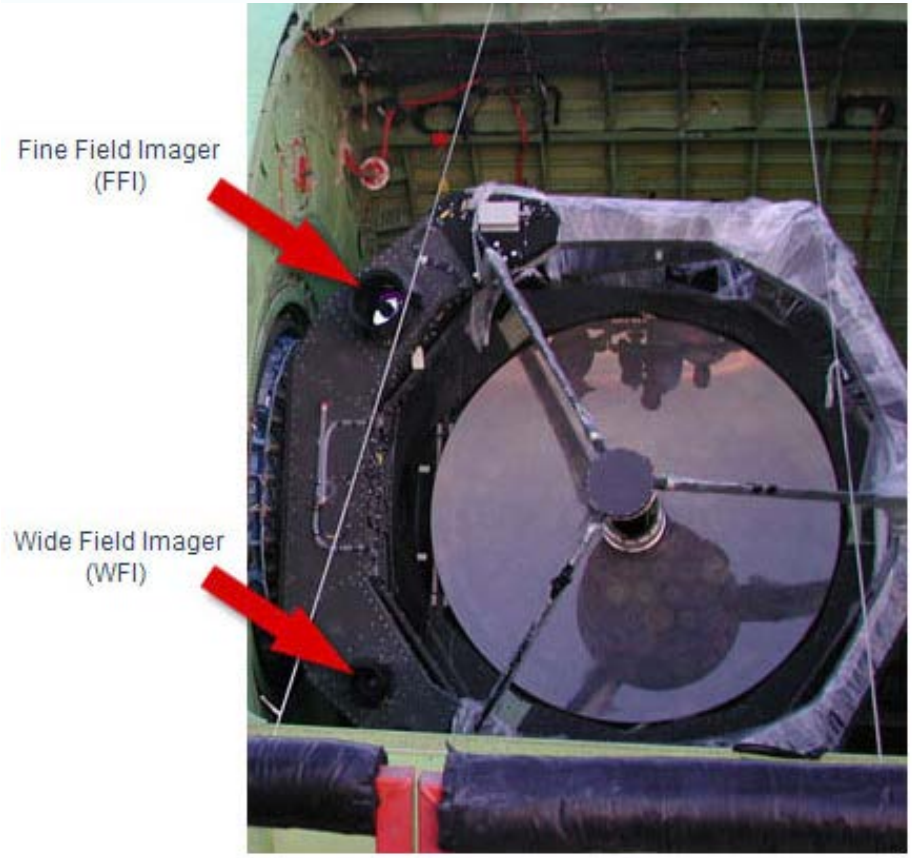
# Why use an EMCCD for slit viewing and guiding?

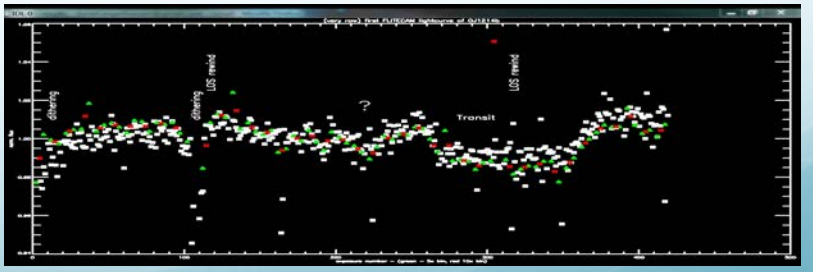
- Placing an object into the entrance slit of the spectrometer requires a near video rate image display to provide feedback to the telescope operator. The faster the object can be placed in the slit the higher the productivity of the spectrometer.
- A large proportion of the observations made with DBSP at Palomar Observatory are of faint objects (>18$^{th}$ magnitude) requiring "blind" offsets for target acquisition.
- Decreasing the number of targets requiring offsets for acquisition improves efficiency.
- Visual verification that the target is in the slit is preferable even when offsets are used.
- EMCCD cameras provide high sensitivity at high speed (30MHz) using EM gain.

# Prior Art
## Stratospheric Observatory for Infrared Astronomy (SOFIA)

- The FPI (Focal Plane Imager) uses a Andor DU 888 EMCCD



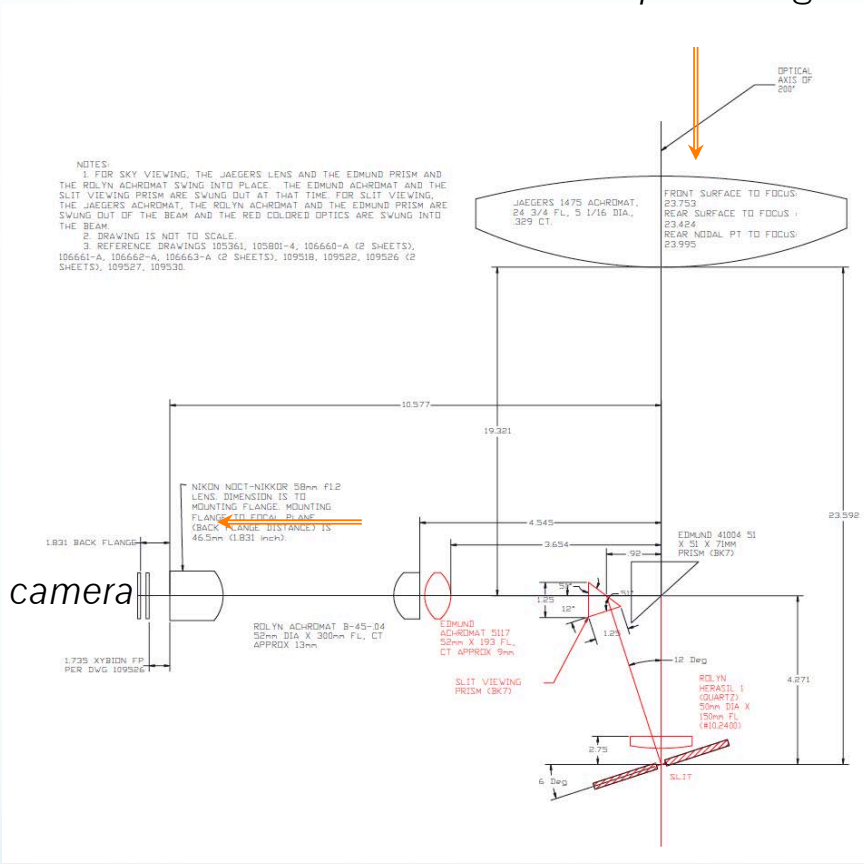

| Parameter | Value or range | | Notes |
|---|---|---|---|
| Imager/CCD: | FFI/WFI Thomson 7888A | FPI E2V CCD201-20 | |
| Array dimensions: | 1024 x 1024 image area | 1024 x 1024 | frame transfer readout |
| Pixel size: | 14 microns | 13 microns | |
| Binning options: | 1x1, 2x2, 4x4 | 1x1, 2x2, 4x4 | 4x4 done off chip for FFI/WFI |
| Integration time: | 10 - 10,000 ms | 1 - 10,000 ms | |
| Data format: | 14-bit 2 MHz or 8-bit 5 MHz | 16-bit 1 MHz or 14-bit 3 MHz or 14-bit 5 MHz | |
| Maximum frame rate: | 8 frames / s | 11 frames / s | 4x4 binning, 5 MHz |
| Peak Q. E.: | 18% at l 550 nm (front illuminated) | 94% at 560nm (back illuminated) | |
| Read noise: | 60 e - = 5 DN | 6 e- at 1 MHz = 9 DN<br>36 e- at 5 MHz = 4 DN | |
| | | | |
| Dark current (-30 ¡C): | 50 e -/s | 0.06 e-/s | New FPI is thermo-electrically cooled, FFI and WFI stratospheric conditions |
| Gain | 12 e - / DN (14 bit, 2 MHz)<br>~600 e- / DN (8 bit, 5 MHz) | 0.7 e- / DN (16 bit, 1 MHz)<br>1.9 e- / DN (14 bit, 3 MHz)<br>8.9 e- / DN (14 bit, 5 MHz) | |
| Saturation | 170,000 -200,000 e - | 80,000 e- | |




During a flight to measure a planetary transit in 2014 of GJ 1214b the FPI was used as an additional science channel for the observations made by FLITECAM (1-5.5 microns) and HIPO (e2v CCD47-20 1024x1024 ).

# DBSP slit viewing optics

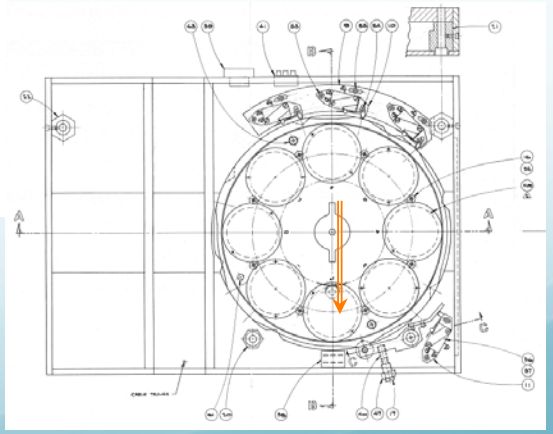
*P200 Telescope Cassegrain Focus*




*Slit viewing camera*

*DBSP Spectrometer*


*DBSP Slit Carousel*



# Slit Viewing Camera

## camera and optical components

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*Andor Ultra DU888 EMCCD Camera*

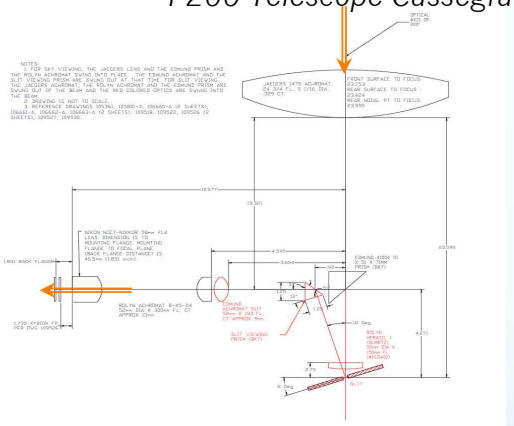
Johnson-Cousins Filter Set
*(open , B, V, R, I, ND2, ND4)*

*Canon EF 50mm f/1.2 lens*



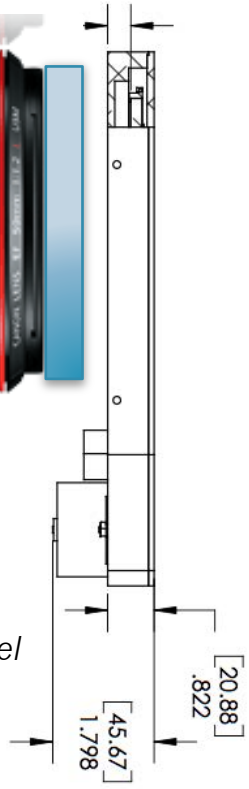
*Birger Engineering*
*Focus/Aperture Control*

*P200 Telescope Cassegrain Focu*



*DBSP Spectrometer*

*Finger Lakes Instrument CFW 2-7 Filter Wheel*



# Physical Connection Diagram for GUIDER and SLIT VIEWING applications

ANDOR Ultra 888 Cameras

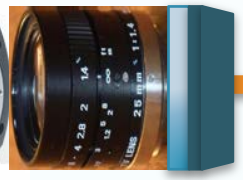
Andor Ultra 888

USB3 to Fiber Adapters

Filter wheel

SLIT Viewing Application
Requires mounting plate
C mount to lens adapter
possible new lens

Cosmicar, 25mm,
1:1.4, Television Lens



Fiber Guider Application
possible mounting plate
requires fiber to lens adapter
possible new lens

Optical Fiber

Fiber Optic Pair

Fiber Optic Pair

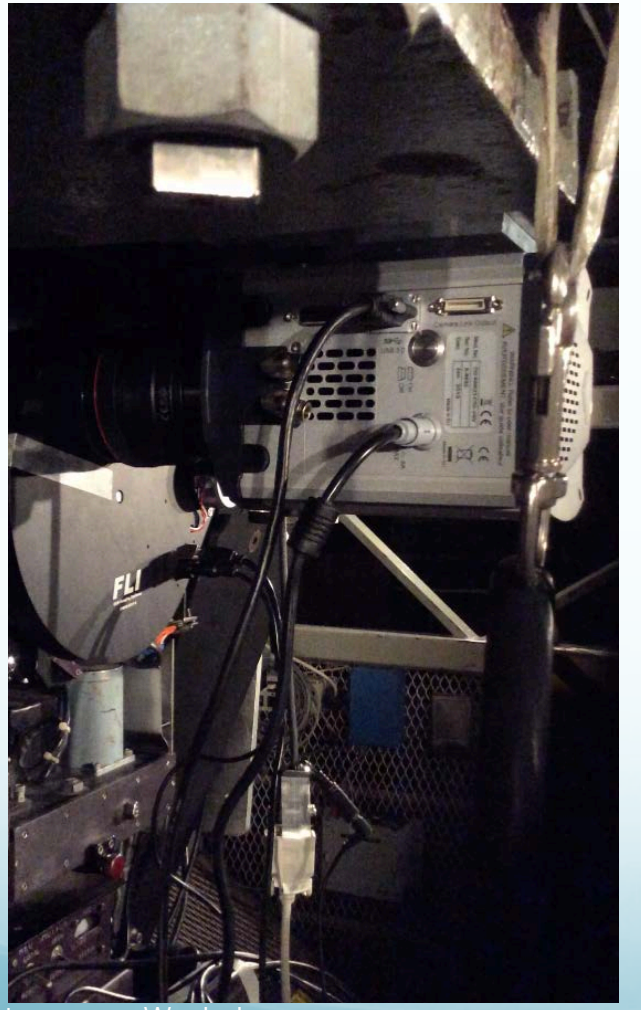
USB 3.0 interface

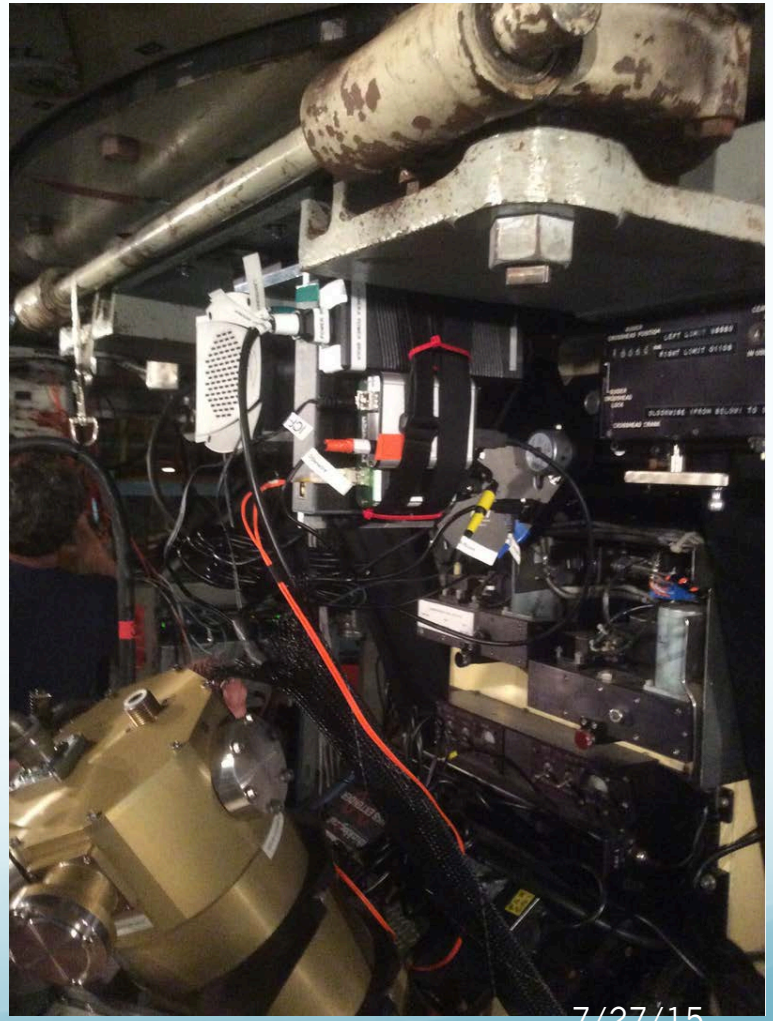
Computers located in the data room
not the Cassegrain cage

Custom LINUX software

System Requirements:
RHEL 6.5 or newer
3.0 Gb RAM, 1Tb drive,
recommended fast quad core or better processor

# Andor Ultra 888 mounted on DBSP in the slit viewing role
# July 22 and 23, 2014



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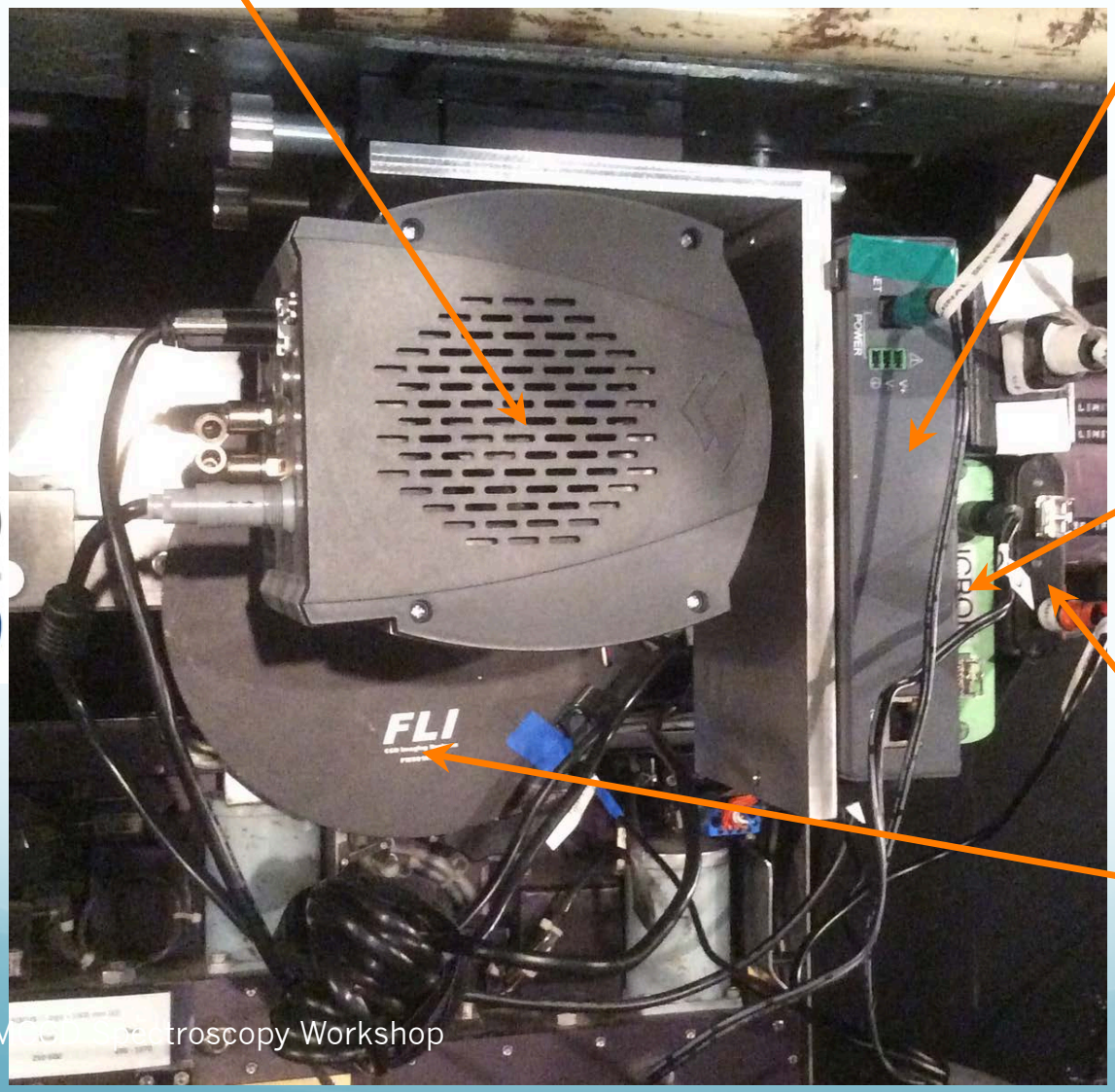
# Andor Ultra 888 mounted on DBSP in the slit viewing role

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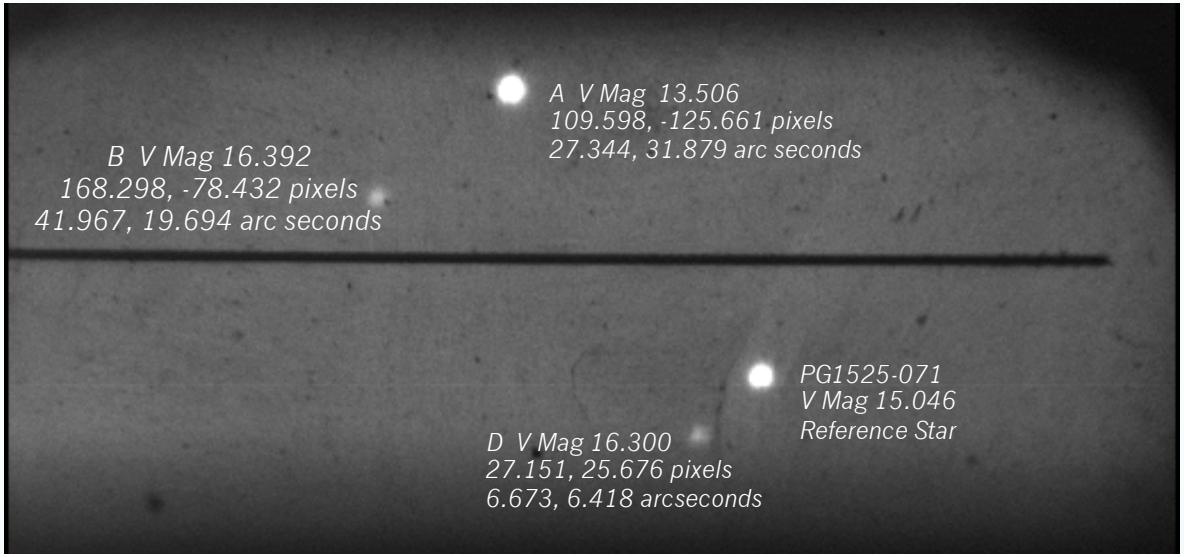
# Calculation of Plate Scale

- Coordinates taken from the UCAC3 catalog for the calculation of offsets in RA and Dec




**Calculation of the Camera Plate Scale**

| Standard Star Designation | RA | DEC | Distance From Reference (arcseconds | dRA (arcseconds) | dDec (arcseconds) |
|---|---|---|---|---|---|
| PG1525-071 - Reference Star | 15:28:11.577 | -07:16:32.93 | 0 | 0 | 0 |
| PG1525-071A | 15:28:13.415 | -07:16:01.05 | 41.999 | 27.344 | 31.879 |
| PG1525-071B | 15:28:14.398 | -07:16:13.23 | 46.359 | 41.967 | 19.694 |
| PG1525-071D | 15:28:12.026 | -07:16:39.35 | 9.259 | 6.673 | -6.418 |

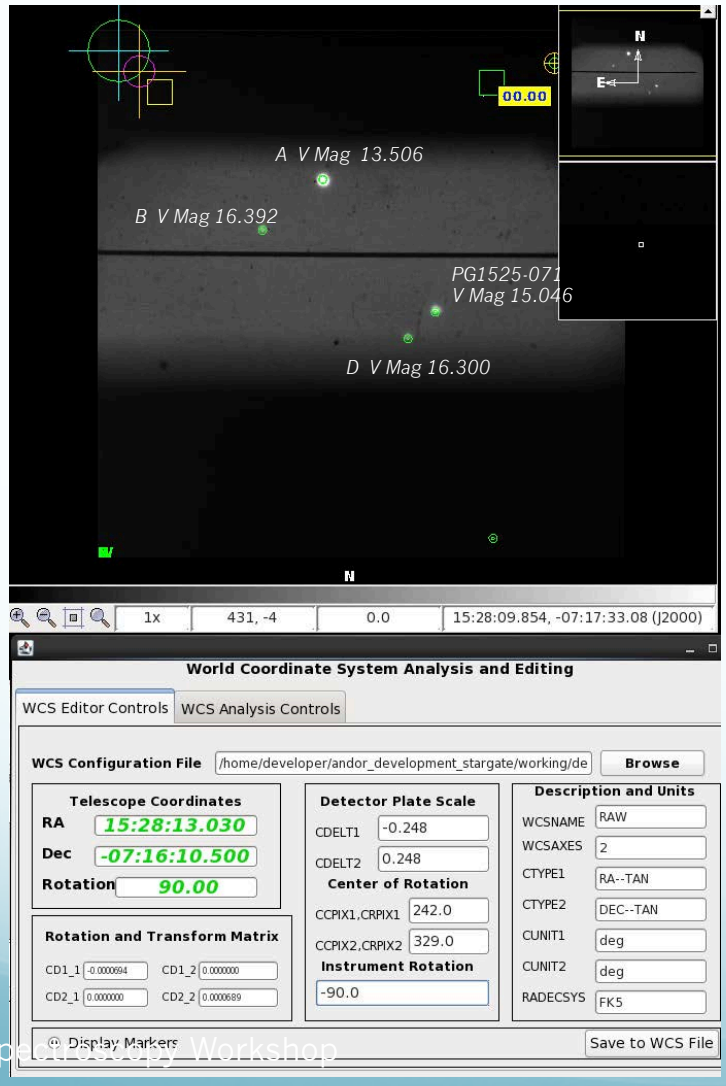
| | Centroid X (pixels) | Centroid Y (pixels) | FWHM X (arcseconds) | FWHM Y (arcseconds) | dX pixels from Ref | dY pixels from Ref | Plate Scale Calculations: arc seconds / pixel dX (arcseconds / pixel) | dY (arcseconds / pixel) |
|---|---|---|---|---|---|---|---|---|
| PG1525-071 - Reference Star | 329.439 | 241.859 | 1.735 | 1.553 | 0 | 0 | | |
| PG1525-071A | 219.841 | 367.52 | 1.71 | 1.553 | 109.598 | -125.661 | 0.249493604 | -0.253690485 |
| PG1525-071B | 161.141 | 320.291 | 1.745 | 1.369 | 168.298 | -78.432 | 0.249361252 | -0.251096491 |
| PG1525-071D | 302.288 | 216.183 | 1.82 | 1.613 | 27.151 | 25.676 | 0.245773636 | -0.249961053 |
| | | | | | | Mean | 0.2482 | -0.2516 |
| | | | | | | Standard Deviation | 0.0021 | 0.0019 |

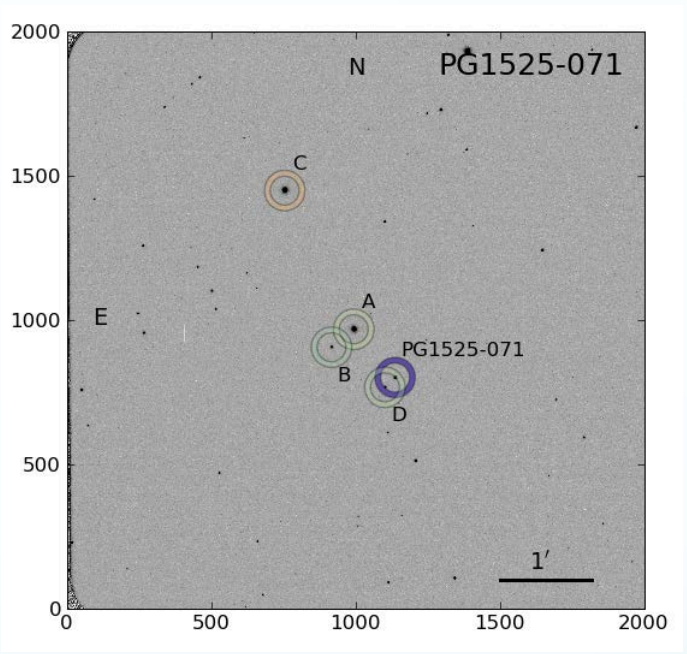
Plate Scale: no binning 0.1249 arc seconds / pixel
2x2 binning 0.2499 arc second / pixel
Note: this agrees with the initial estimate of 0.124

# Approximate World Coordinate System fit to standard photometry field: PG1525-071
# CATALOG OVERLAY PRECISELY FITS POSITION OF STARS IN THE IMAGE
## January 28, 2015 Jennifer W Milburn

*Mapping = INVERT_X, Rotation = 90 clockwise*

*Approximate Plate Scale = 0.124 arcsec/pixel (no binning) 0.248 arcsec/pixel binned 2x2*




| Star | V | B-V | U-B | V-R | V-I | n | m |
|---|---|---|---|---|---|---|---|
| PG1525-071 | 15.046±.0027 | -0.211±.0005 | -1.177±.0027 | -0.068±.0020 | +0.012±.0020 | 20 | 13 |
| PG1525-071A | 13.506±.0008 | +0.773±.0015 | +0.282±.0019 | +0.437±.0006 | +0.421±.0024 | 15 | 8 |
| PG1525-071B | 16.392±.0039 | +0.729±.0043 | +0.141±.0097 | +0.450±.0037 | +0.387±.0066 | 17 | 8 |
| PG1525-071C | 13.519±.0007 | +1.116±.0028 | +1.073±.0052 | +0.593±.0010 | +0.509±.0015 | 16 | 9 |
| PG1525-071D | 16.300±.0021 | +0.393±.0714 | +0.224±.0316 | +0.405±.0108 | +0.343±.0196 | 15 | 8 |

n: number of times star was observed
m: number of nights star was observed

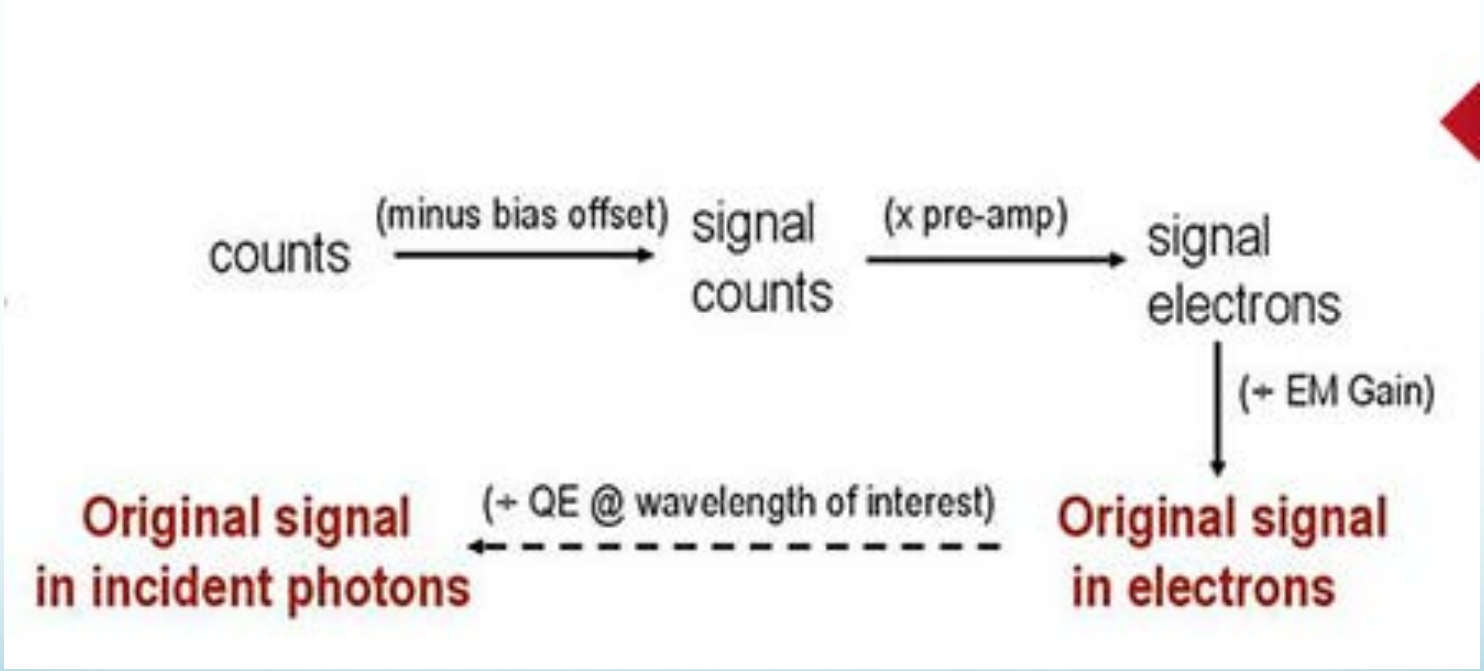
The circle around a star indicates the U-B-colour.

http://www.not.iac.es/instruments/stancam/photstd/

# Andor Ultra DU 888 Calculation of photons/second

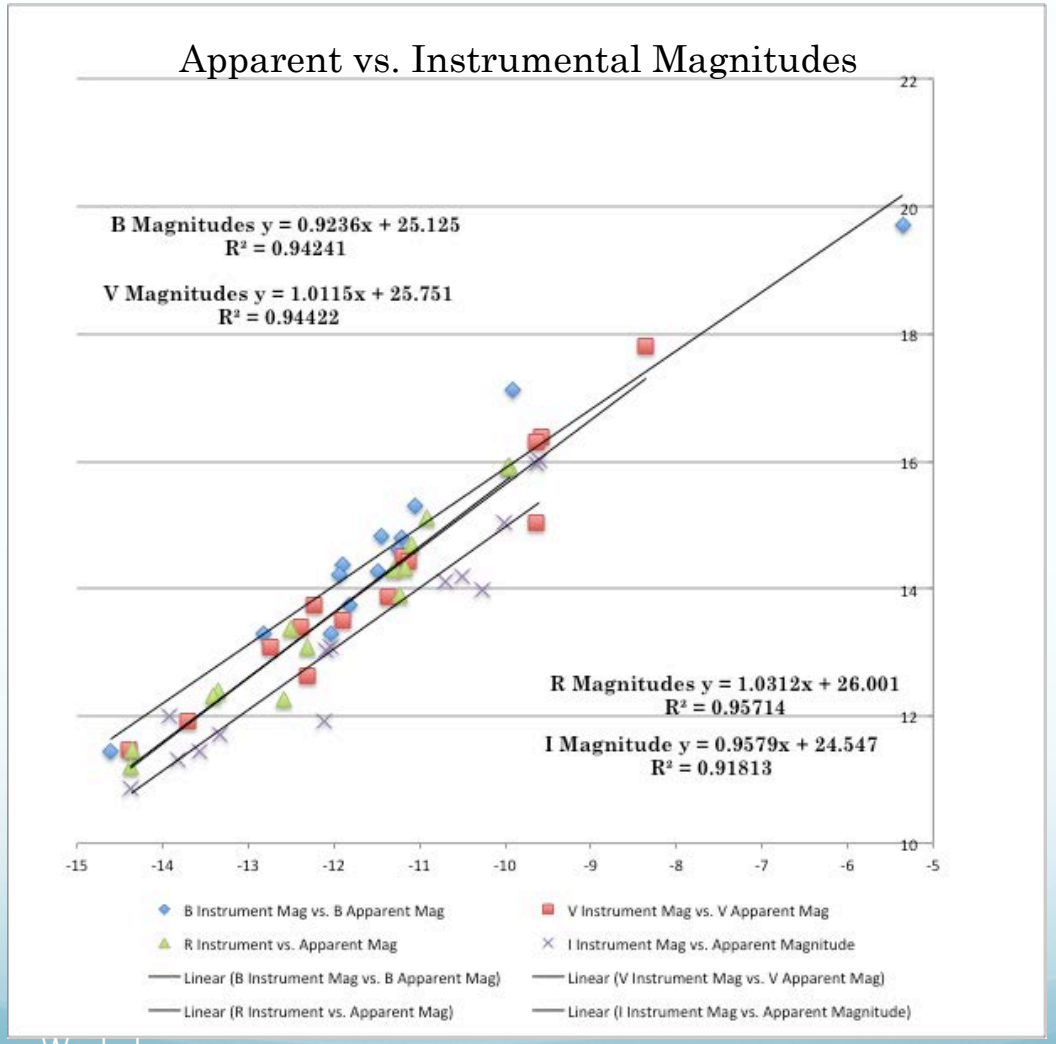
- Calculation of photons/second for the EM gain amplifier

Electrons per DU = 18.7 for 30MHz horizontal shift amplifier, gain 1, source camera performance verification document.

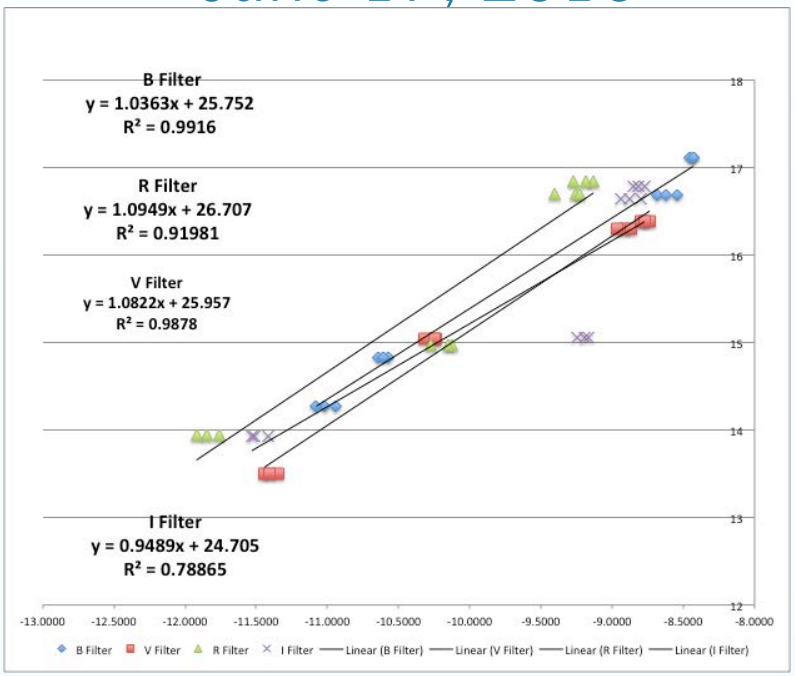



Quantum Efficiency: from Andor quantum efficiency graph

# Apparent vs. Instrument Magnitudes for B,V,R and I Filters
# Andor DU888 Ultra EMCCD Slit Viewing Camera
# March 26, 2015



## Apparent vs. Instrument Magnitudes for B,V,R and I Filters correct for Airmass
## Andor DU888 Ultra EMCCD Slit Viewing Camera
# June 17, 2015

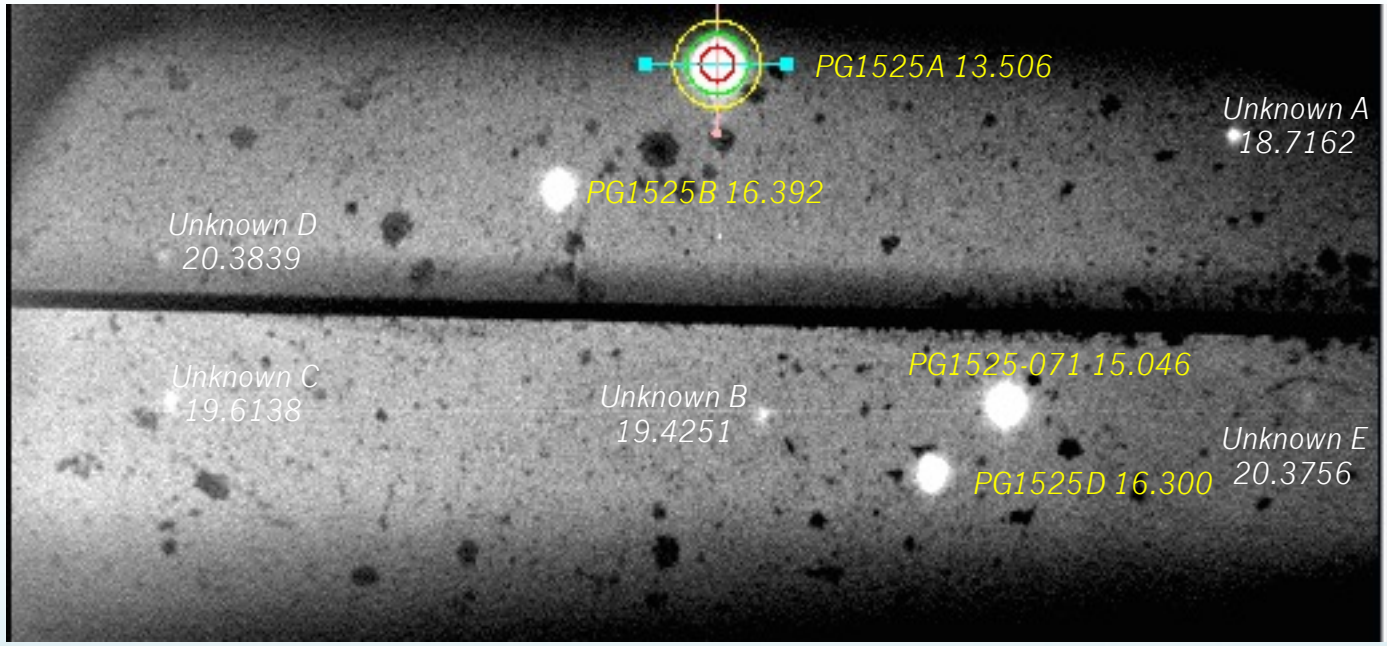



**Zero Point Calculation Comparison**

| | *January 28, 2015* | *March 26, 2015* | *June 17, 2015* |
|---|---|---|---|
| **Landolt B** | 25.779 | 25.125 | 25.752 |
| **Landolt V** | 25.728 | 25.751 | 25.957 |
| **Landolt R** | 27.158 | 25.932 | 26.707 |
| **Landolt I** | 25.035 | 24.547 | 24.705 |
| | ***Not Photometric*** | ***Photometric*** | ***Airmass Corrected*** |

# Standard Fields with Multiple Standard Stars

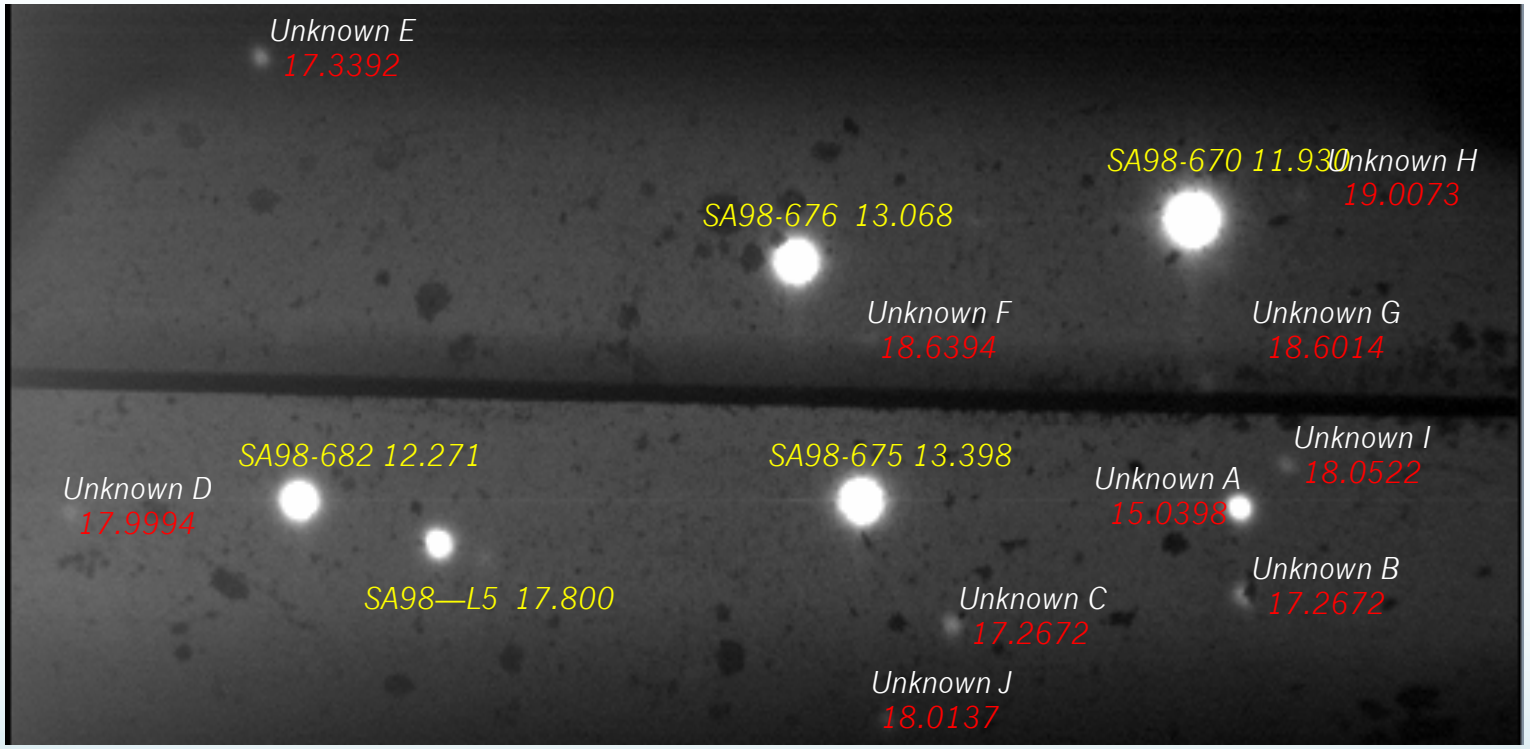
## PG1525-071 Landolt Standard Field: V Magnitudes




This standard field has been imaged and analyzed using each of the Sloan filters during each of the commissioning observing runs

# Standard Fields with Multiple Standard Stars

## SA98-670 Landolt Standard Field: V Magnitudes

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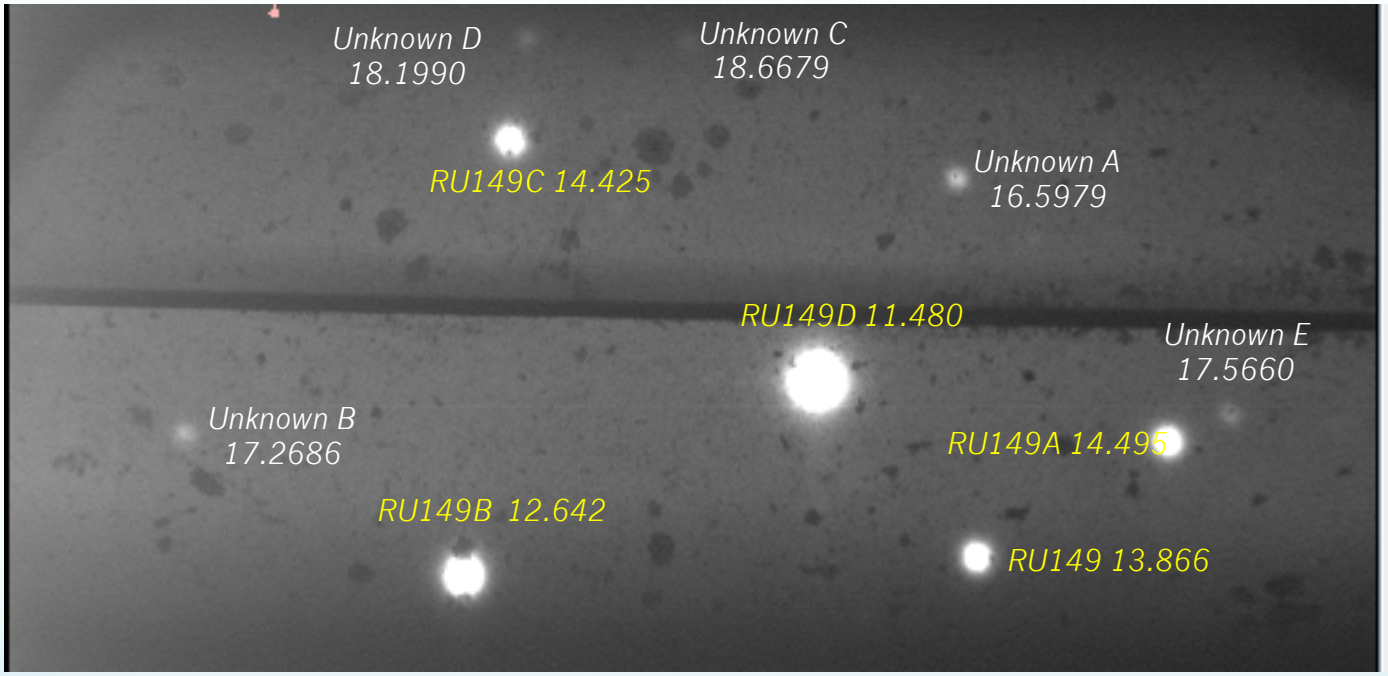
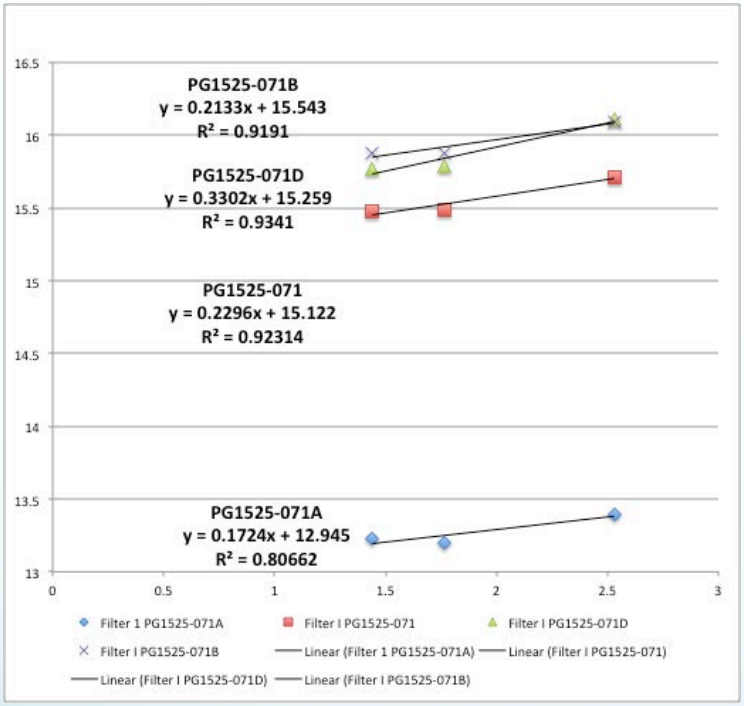
# Standard Fields with Multiple Standard Stars
## RU149 Landolt Standard Field: V Magnitudes

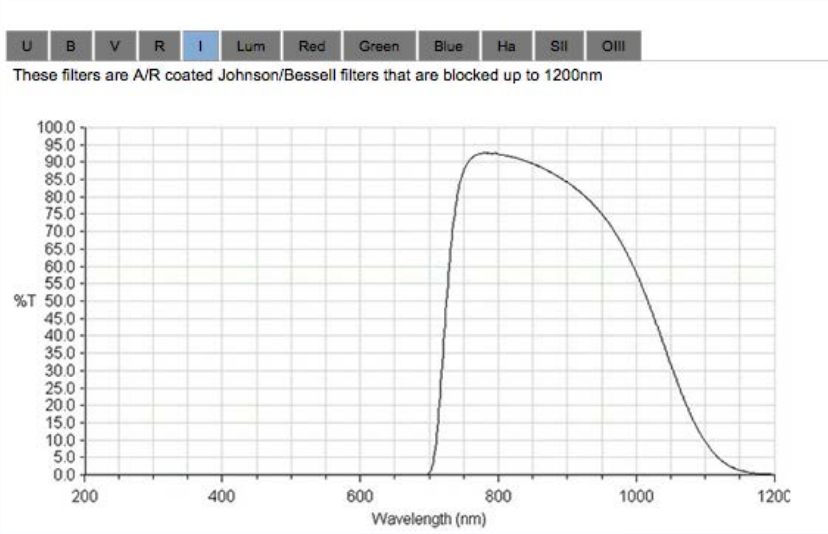


# Observing Run: June 17, 2015

## Example determination of Atmospheric Absorption Coefficients

### *I Landolt Filter*




| | *I Filter* |
|---|---|
| **PG1525-071A** | 0.1724 |
| **PG1525-071** | 0.2296 |
| **PG1525-071D** | 0.3302 |
| **PG1525-071B** | 0.2133 |
| **Mean** | **0.2364** |
| **Standard Deviation** | 0.0670 |

*magnitudes / airmass*

# Determination of first order extinction coefficients for each filter

## Based on observations of 4 stars in the PG1525-071 standard field at 3 airmass values

Typical values for the Johnson-Cousins UBVRI Filters

| passband | k |
|---|---|
| U | 0.6 |
| B | 0.4 |
| V | 0.2 |
| R | 0.1 |
| I | 0.08 |

**Summary of first order extinction coefficients determined June 29, 2015**

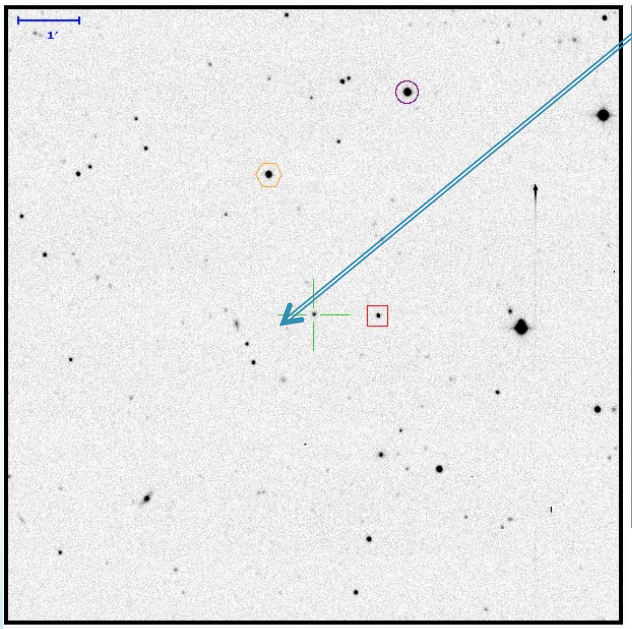
| | *Blue Filter* | *V Filter* | *Red Filter* | *I Filter* | |
|---|---|---|---|---|---|
| **PG1525-071A** | 0.1773 | 0.2511 | 0.3656 | 0.1724 | |
| **PG1525-071** | 0.2795 | 0.3046 | 0.4312 | 0.2296 | |
| **PG1525-071D** | 0.4399 | 0.3579 | 0.4824 | 0.3302 | |
| **PG1525-071B** | 0.3220 | 0.2732 | 0.3975 | 0.2133 | |
| **Mean** | **0.3047** | **0.2967** | **0.4192** | **0.2364** | *magnitudes/airmass* |
| **Standard Deviation** | 0.1087 | 0.0463 | 0.0499 | 0.0670 | *magnitudes/airmass* |

**Note: The pattern of calculated extinction coefficients suggests that there are systematic effects present in the data**
**The second data point is always below the fitted line suggesting that at least one of the points is non-photometric**

# Observation of 20th magnitude PTF object

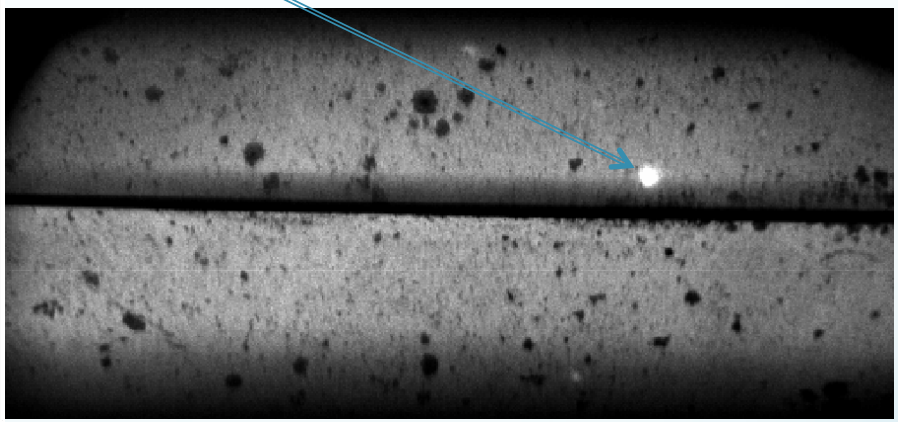
## note: object may be brightening and the reported magnitude may be inaccurate

PTF Target 15aal  Magnitude 19.99



| Candidate (green cross) | | |
|---|---|---|
| RA | 12:28:16.108<br>187.067115 | (J2000) |
| DEC | +19:38:34.26<br>19.642849 | |
| Mag (sub) | 19.99 ± 0.15 | g-band |
| **Offset Star S1 (red box)** | | |
| RA | 12:28:11.576 | (J2000) |
| DEC | +19:38:33.73 | |
| Mag (ref) | 18.26 ± 0.02 | g-band |
| Offset | 63.4" (PA= 89.5) | |
| **Offset Star S2 (orange hex)** | | |
| RA | 12:28:19.361 | (J2000) |
| DEC | +19:40:52.95 | |
| Mag (ref) | 16.02 ± 0.01 | g-band |
| Offset | 144.6" (PA=198.3) | |
| **Offset Star S3 (purple circle)** | | |
| RA | 12:28:09.645 | (J2000) |
| DEC | +19:42:16.10 | |
| Mag (ref) | 15.18 ± 0.00 | g-band |
| Offset | 237.2" (PA=157.6) | |

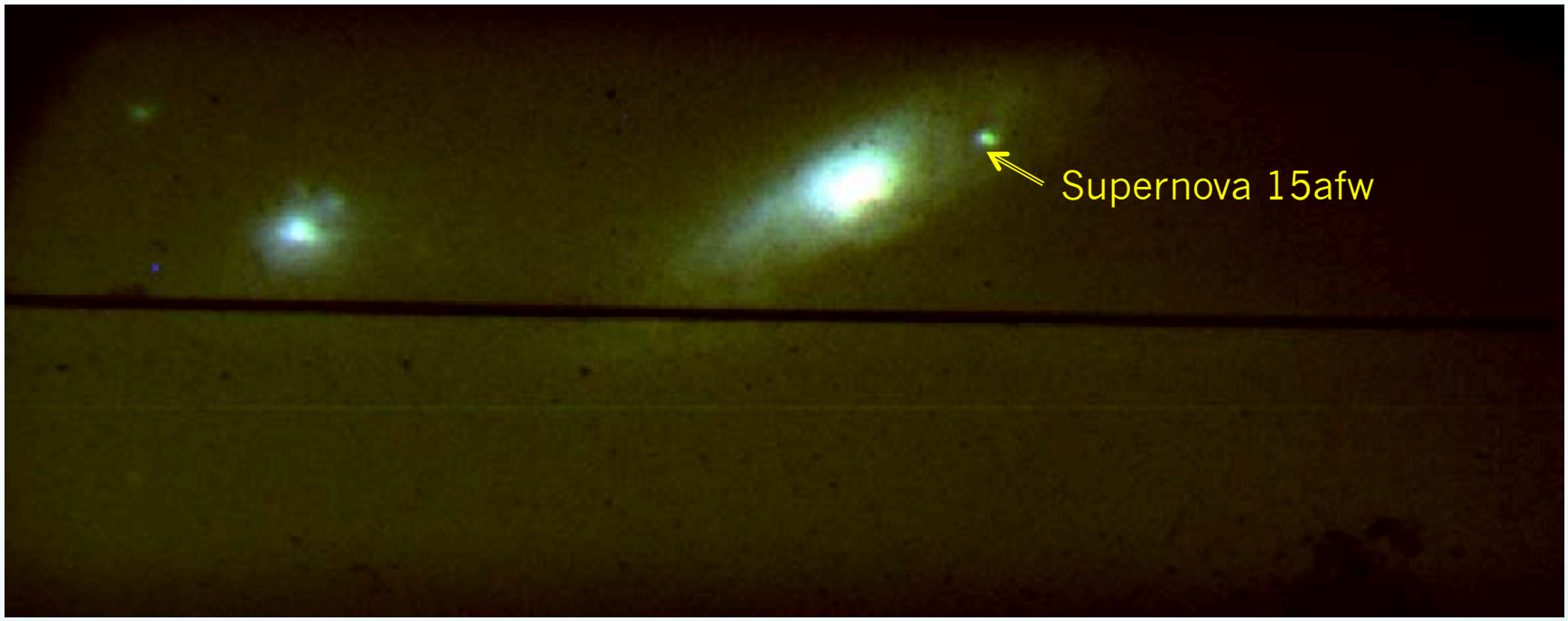
New image shown ($g_{lim}$ = 21.3). N is up, E is left.



# PTF Target 15afw March 9, 2015

## Photometry determined using the Andor DU888 Ultra EMCCD Slit Viewing Camera

## PTF calculated magnitude G=19.2

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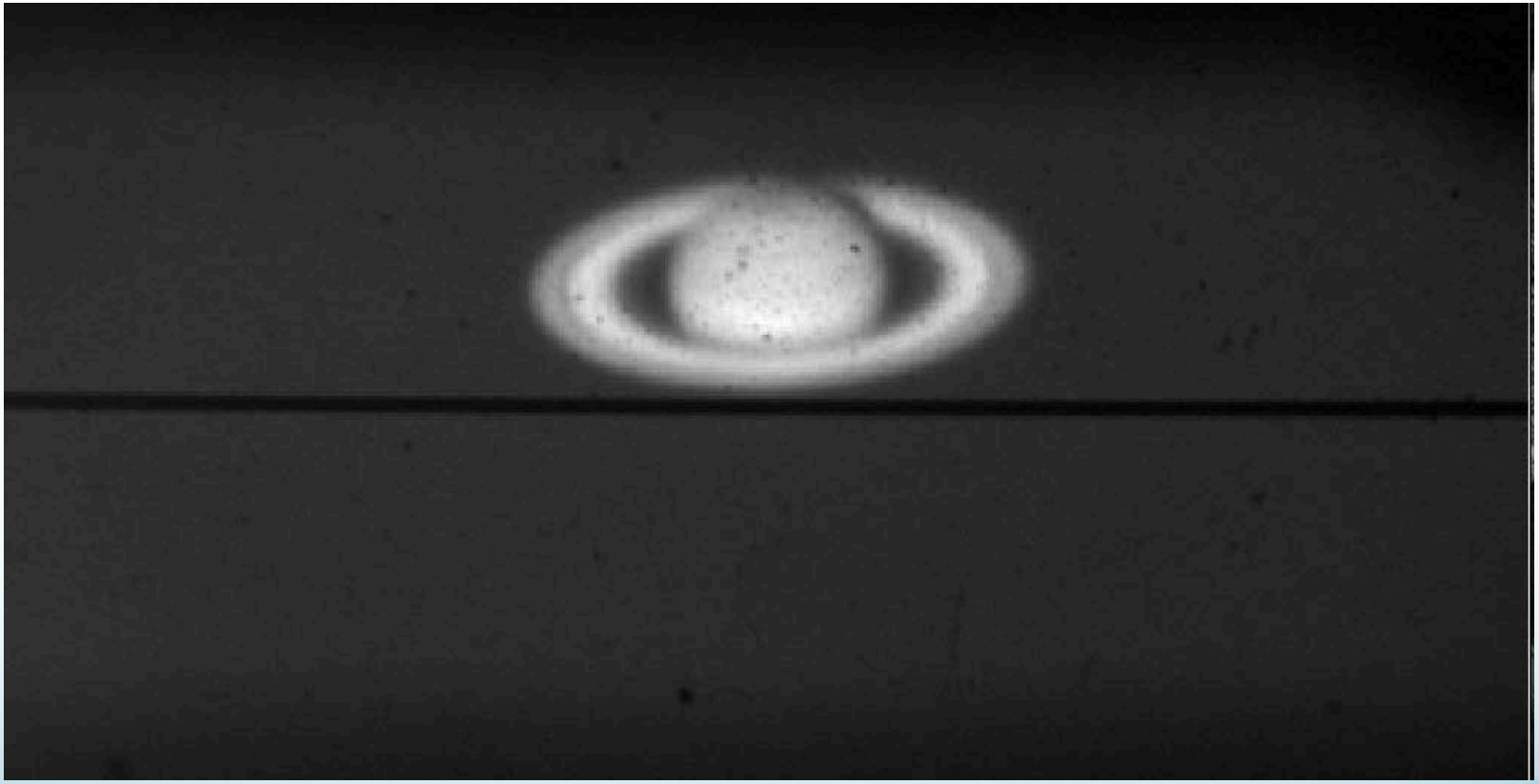
***PTF Target 15afw March 9, 2015 Photometry***

| | *Apparent Magnitude* | *Error* |
|---|---|---|
| B | 18.052 | 0.083 |
| V | 18.158 | 0.071 |
| R | 17.978 | 0.078 |
| I | 16.918 | 0.102 |

# Saturn imaged by the Andor Ultra 888

(ND4 filter) Visual Magnitude +1.47 to -0.24

January 28, 2015 Jennifer Milburn



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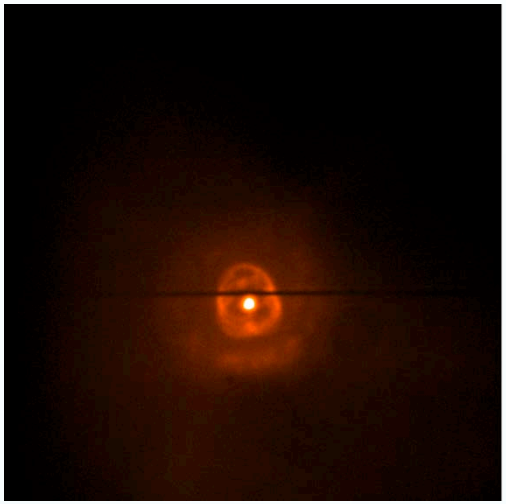
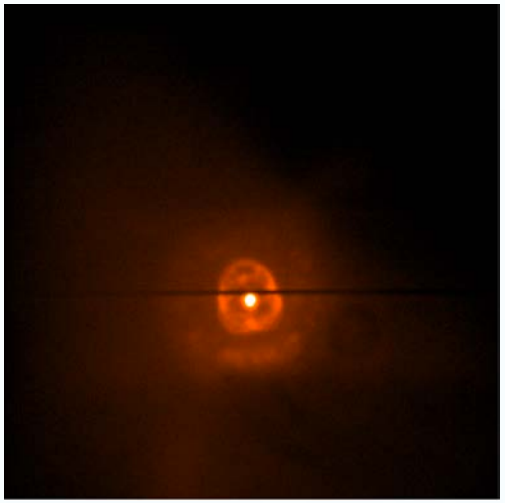
# Eskimo Nebula – Andor Ultra 888 EMCCD

## The "Slit View" camera can provide excellent astronomical images with well characterized photometry

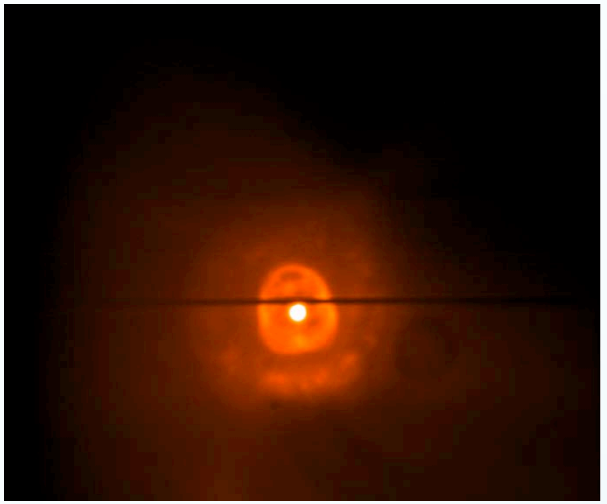
1024x1024 image



512x512 image, binned 2x2



Very deep image but blurred by
Motion and turbulence
~25,000 images, 0.1 sec integration



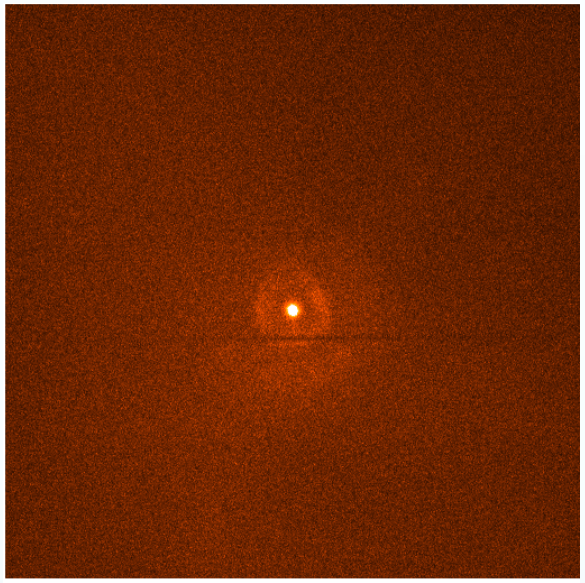
Eskimo Nebula
100 frames, 0.1 seconds per frame
10.0 seconds total exposure time
Apparent Magnitude: 10.8 in B

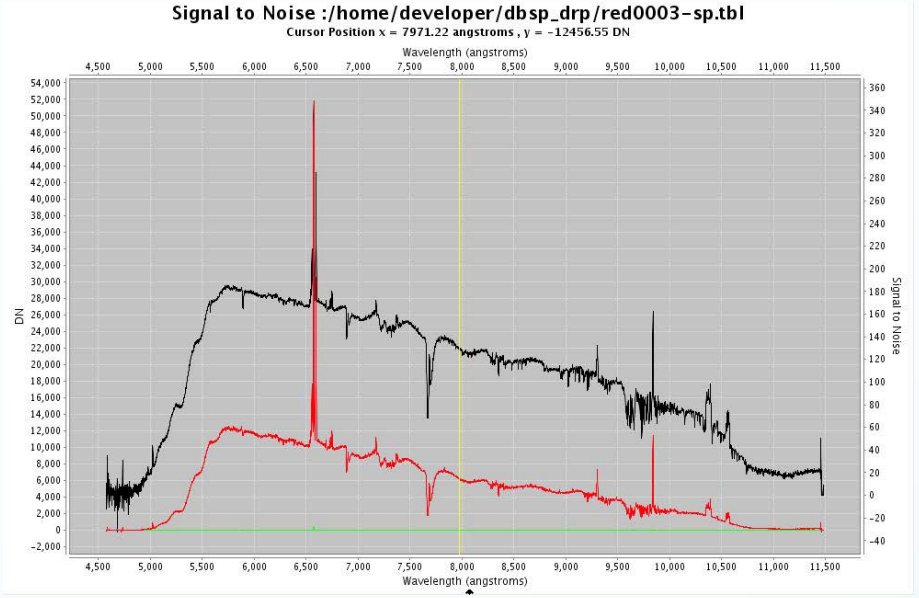
**Right ascension** $07^h\ 29^m\ 10.7669^s$[1]
**Declination** +20° 54′ 42.488″ [1]

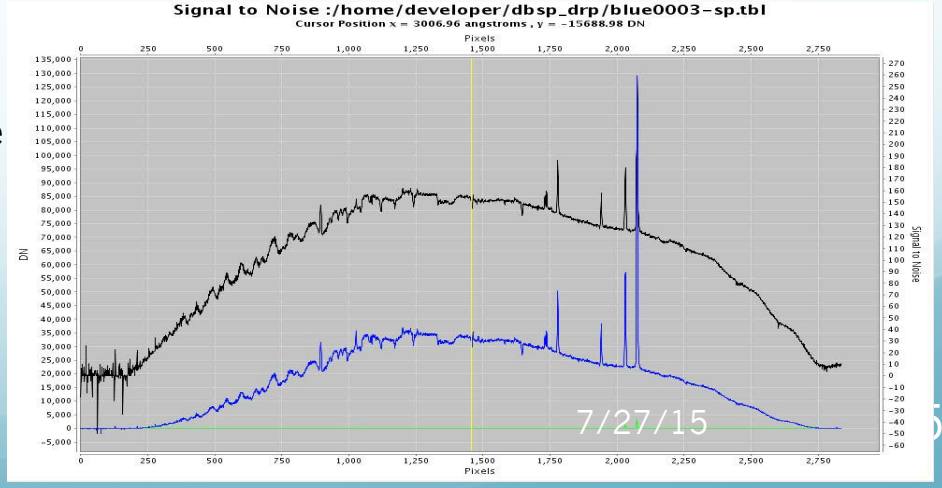
Reference NASA image (Hubble)

# Eskimo Nebula – Andor Ultra 888 EMCCD

DBSP Spectrum taken 10-25-2014 of the central star in the Eskimo Nebula 300 seconds exposure






Eskimo Nebula
100 frames, 0.1 seconds per frame
Individual frame
Apparent Magnitude: 10.8 in B

# Performance Summary

- *World Coordinate System:*
  - *Mapping = INVERT_X,*
  - *Instrument Rotation = 90 clockwise*
  - *Center of Rotation : X = 242 Y = 329 (binned 2x2)*
  - *Approximate Plate Scale = 0.1249 arcsec/pixel (no binning) 0.2499 arcsec/pixel binned 2x2*
- *Zero Point Magnitudes (Johnson-Cousins Filters – Landolt standard stars)*
  - *B = 25.75*
  - *V = 25.96*
  - *R = 26.71*
  - *I = 24.71*
- *Limiting Magnitudes – 19$^{th+}$ magnitude on bright nights, 20$^{th+}$ magnitude on dark nights with good seeing*
- *Bright objects can easily be imaged by decreasing the exposure time (minimum = 0.1 milliseconds) and using filters (ND2 or ND4) (e.g. Saturn -0.24 Magnitude)*
- *Limiting magnitude determined by sky brightness and seeing.*
- *The very poor condition of the slit mirror surface (particularly the heavily used 1.5 arcseconds slit) is partially responsible for the current instrument performance.*