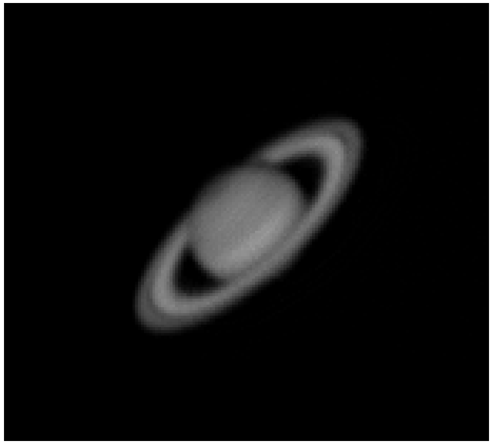
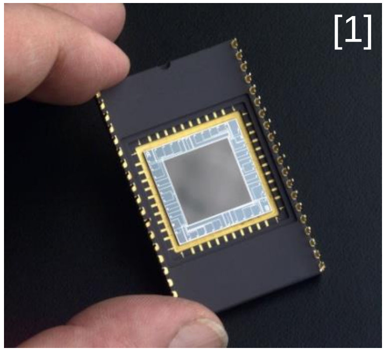
7 Astronomy with Cameras



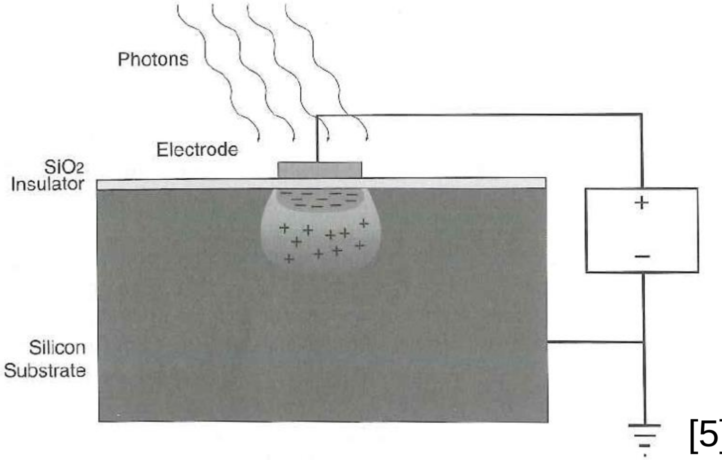
7.1 Introduction



- The eye as a sensor
  - Efficiency: ~ 15% at 505 nm
  - Integration time: ~ 0.1 – 0.2 s
- CCD Chips
  - Efficiency: depending on sensor and wavelength, in the visual spectrum its typically some 30% to 90%
  - Integration time: driven by sensor, ranging from μs to hours
- Today‘s modern astronomy solely uses CCD sensors and fully digital processing chains, humans are only operators
- Advantages
  - A sensor can be optimized for specific wavelengths and applications
  - Repeatability of read out, e.g. the images become comparable
  - High sensitivity and long integration times
  - Digital image processing allows for sophisticated signal reconstruction

7.2 CCD Cameras

- Scheme of a single CCD element
  - On top of a doped silicon substrate (semi conductor) lies a light-transmissive layer of insulation
  - Applying a voltage to the electrode located above insulation creates an electric potential well in the silicon
  - Incoming photons release electrons in the silicon which move towards the electrode due to the potential well. The process is proportional to the amount of incoming photons and their energy (∝ wavelength).



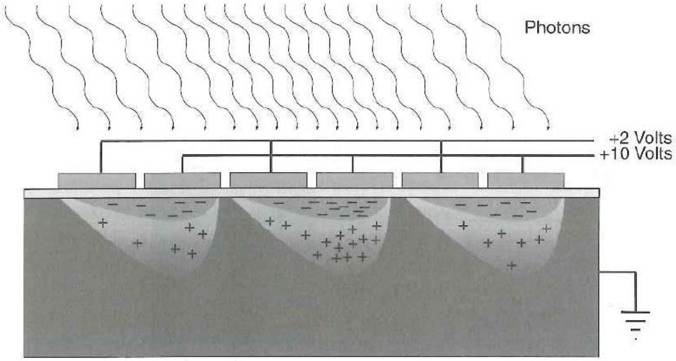
[5]

The size of CCD element determines its efficiency

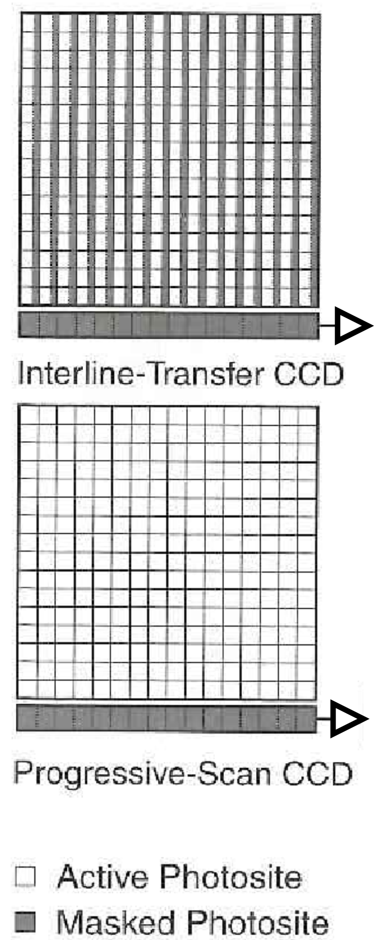
- Larger surface → more photons per area → higher sensitivity
- More electrons can be gathered if the substrate is larger (mitigates blooming)

However, larger CCD elements mean less resolution (for a given sensor size), hence a balance is needed. Typical CCD elements have a size of 5 – 25 µm.

7.2 CCD Cameras



- CCD elements arranged in matrix become a spatial sensor
- Changes in the voltage enables the transportation of the gathered electrons across the elements → charge transfer
- Electrons are registered and digitized (A/D conversion)



Interline Transfer CCD

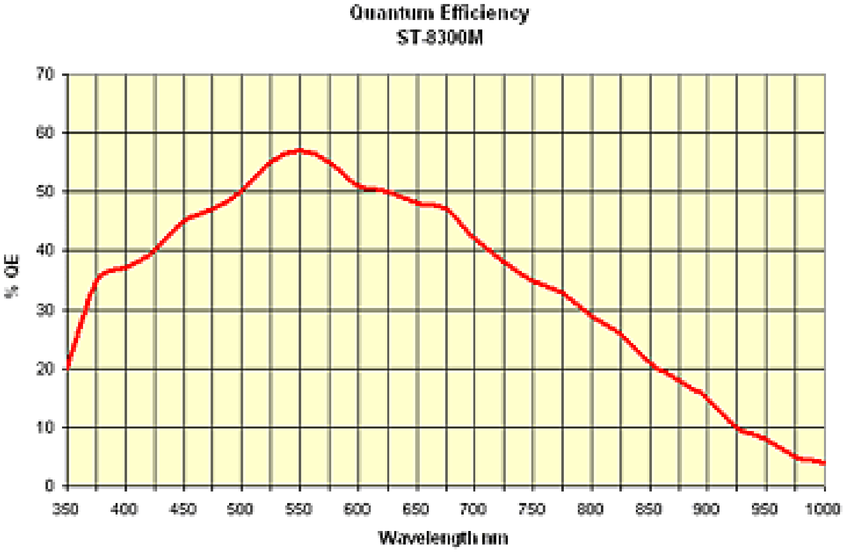
- Charge transfer to the opaque adjacent columns
- Transfer to serial read-out register and A/D conversion
- Continuous process, very fast → video cameras
- Sensor surface only partly usable

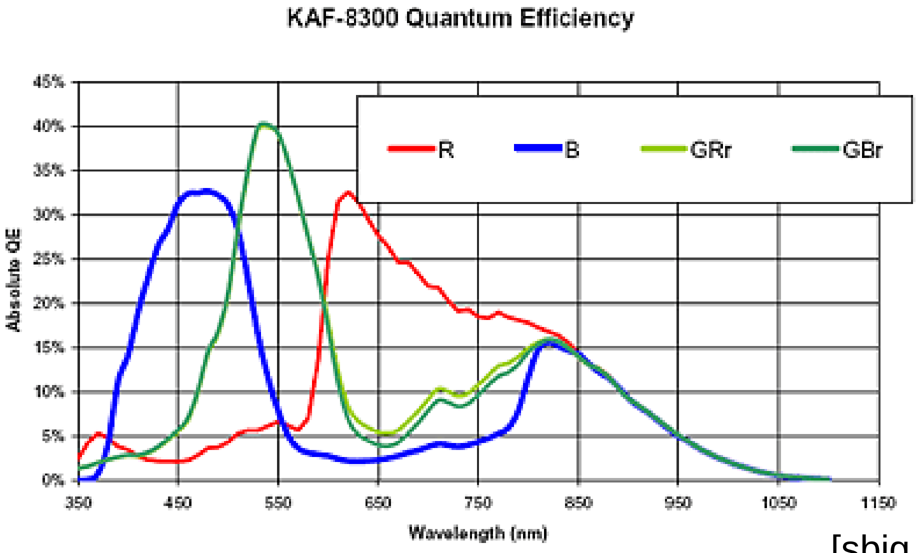
Progressive-Scan CCD

- Transfer to serial register on a line by line basis
- Serial read-out and A/D conv.
- Usually a mechanical shutter is need to allow the read-out
- Next exposure only possible if the sensor read-out has been fully completed
- Typical for the CCD sensors used in astronomy

7.2 CCD Cameras

- The amount of photons detectable by the CCD sensor changes with the quantization and hence with the wavelength
- This property of a sensor across the wavelengths is illustrated by the quantum efficiency (QE) diagram
- Many CCD sensors reach the maximum QE for the red wavelength (650 nm)
- Dedicated astrocameras usually don't come with on-chip filters; to gather light of a certain wavelength one inserts optical filters into the light path

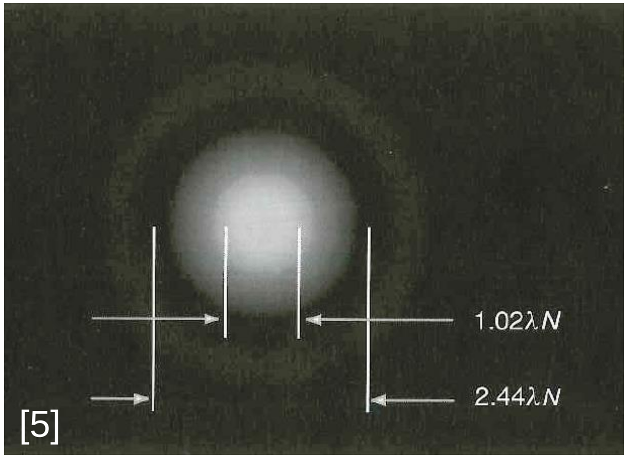




[sbig.de]

7.3 Theoretical limit in spatial resolution

- The limit in spatial resolution of a telescope is driven by the size of the aperture *D* and the wavelength λ (cf. Dawes-formula)
- If the wavelike nature of light becomes visible in the image of a point source the optical system has reached the diffraction limit
- The error free image of point source captured in a circular aperture is the Airy disk having a central peak and concentric rings



Size of first minimum (1st ring):

$$\rho\ [rad] = 2.44\frac{\lambda}{D} \qquad \rho\ [m] = 2.44\frac{\lambda}{D} f_{Ob}$$

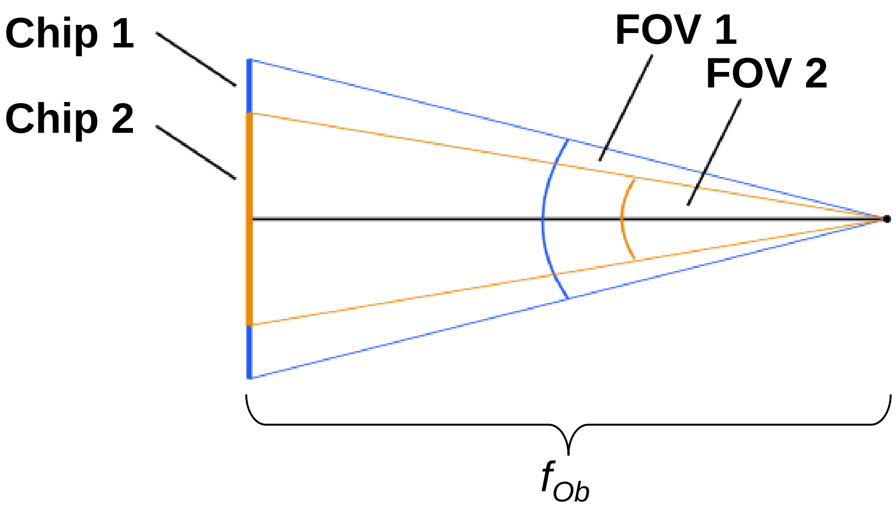
Full-Width at Half-Maximum (FWHM):

$$\rho\ [rad] = 1.02\frac{\lambda}{D} \qquad \rho\ [m] = 1.02\frac{\lambda}{D} f_{Ob}$$

To exploit the resolution of a telescope the camera sampling requires FWHM/2

7.3 Field of View and Mapping Unit

- The field of view of a CCD sensor is driven by its size *s* and the focal length of the objective f_{ob}



Field of View

$$FOV = 2 * \text{atan}\left(\frac{s}{2f_{ob}}\right)$$

s ...sensor size; for rectangular sensors s = length and width

- The size of a CCD pixel determines the sampling
  - Mapping unit: arcseconds per pixel
  - Derived from the FOV or directly from the pixel size of a camera
  - The focal length is the overall driver

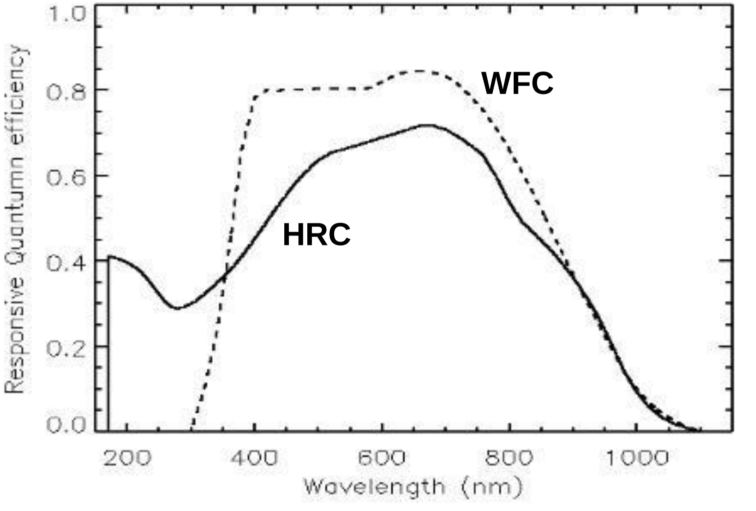
Mapping Unit (sampling)

$$M = 2 * \text{atan}\left(\frac{s_{Px}}{2f_{Ob}}\right)$$

s_{Px} ...pixel size

7.3 Example: Hubble Space Telescope

- Telescope parameters
  - Focal length: f_{Ob} = 57.6 m
  - Aperture: D = 2.4 m
- Wide Field Camera (WFC)
  - Resolution: 4096 x 4096 Px
  - Pixel size: 15 µm
  - QE: ~ 80% @ visual



[http://www.stsci.edu/hst/acs]

7.5 TUM Telescope: 4 in 1

- The EdgeHD 11 of TUM provides 4 different focal lengths

Hyperstar:
f/2, 560 mm

- The secondary is replaced by the Hyperstar corrector
- Only the spherical primary → f/2
- Aberrations are controlled for sensors ≤ 24 x 16 mm

[2]

Default:
f/10, 2800 mm

Barlow 2x:
f/20, 5600 mm

Shapley 0.7x:
f/7, 1960 mm

[2]

Proportionality of aperture vs. integration time: $t \propto \left(\frac{f_{Ob}}{D}\right)^2$

7.5 TUM Telescope: 4 in 1

- Field of view and mapping unit:

[3]

Guppy Pro F-031:

- Sensor size: 3.7 x 2.8 mm
- Pixel size: 5.6 µm
- Theoretical resolution of the EdgeHD 11: 0.45"@600nm

	FOV [']	M [''/px]	rel. Exp.
f/10	4.54 x 3.44	0.41	1
f/20	2.27 x 1.72	0.21	4
f/7	6.49 x 4.91	0.59	1/2
f/2	22.7 x 17.2	2.06	1/25

[4]

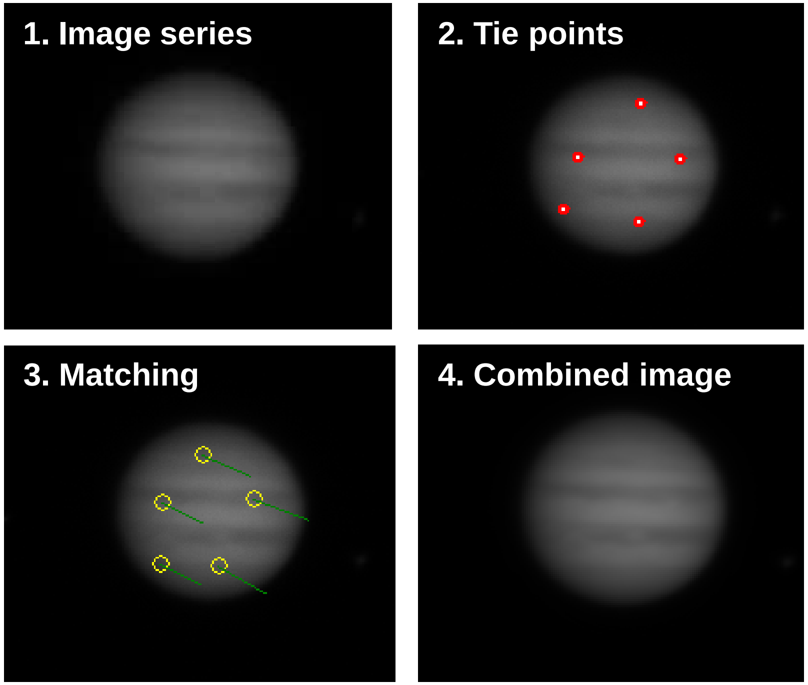
FLI ML 8300:

- Sensor size: 18.0 x 13.5 mm
- Pixel size: 5.4 µm
- Theoretical resolution of the EdgeHD 11: 0.41"@540nm

	FOV [°]	M [''/px]	rel. Exp.
f/10	0.37 x 0.28	0.40	1
f/20	0.18 x 0.14	0.20	4
f/7	0.53 x 0.39	0.57	1/2
f/2	1.84 x 1.38	1.99	1/25

7.6 Image processing using „Lucky Imaging“

- The atmospheric seeing limits the telescope resolution to some 3-4“, hence larger telescopes can‘t benefit from their aperture in terms of resolution
- With the „Lucky Imaging“ technique we can eliminate the seeing when observing sufficiently bright objects (planets, Moon, Sun, double stars …)
- Basic principle:
  - Take a large series of lossless images with a sensitive high-rate camera (webcam)
  - Co-register the images to a consistent stack (tie points)
  - Reduce the stack for the *n* best images
  - Combine the *n* images for the best signal image, e.g. by averaging, addition,…
  - Post-process the combined image, e.g. with Wavelets sharpening



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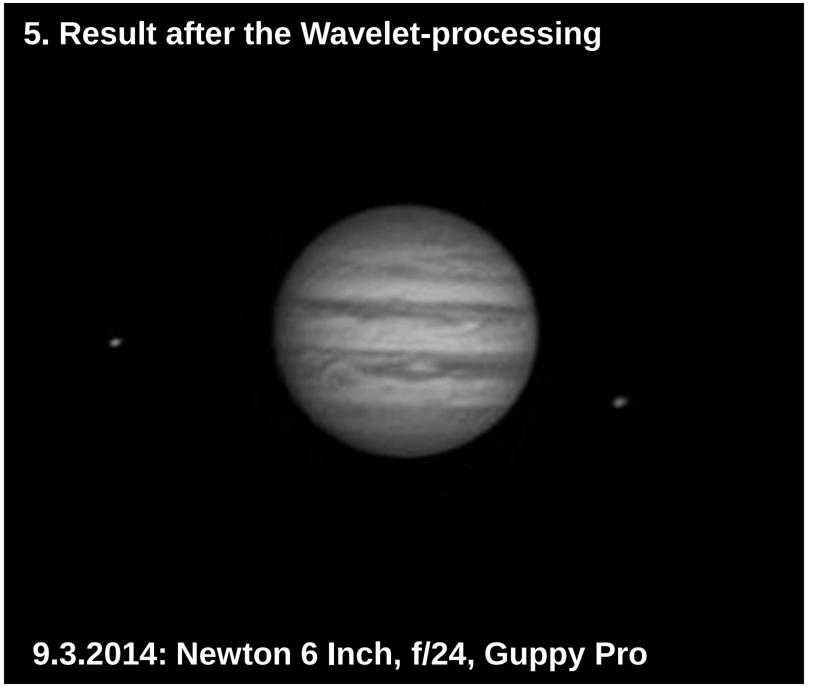
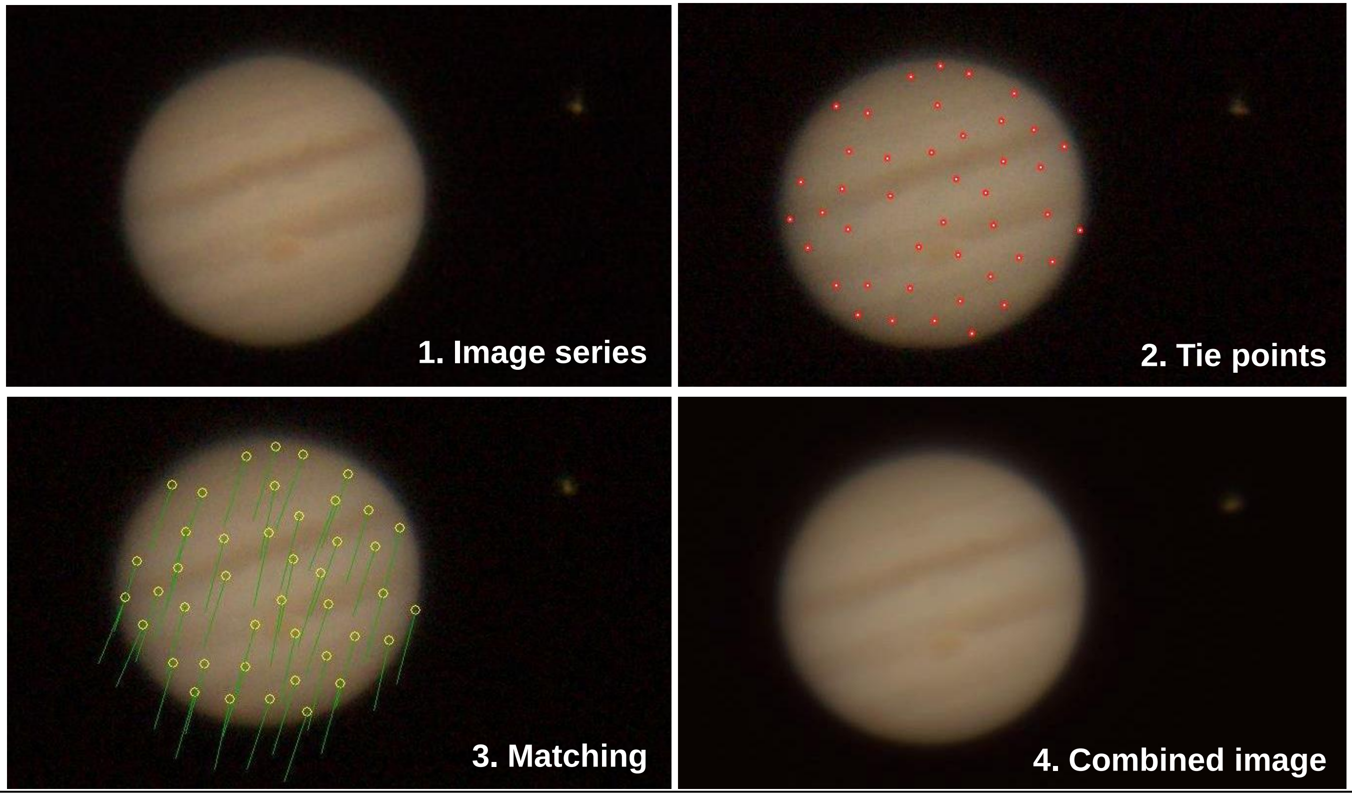


7.6 Image processing using „Lucky Imaging“

- The principle also works for ordinary photographic cameras and even with JPEGs, but raw-imaging capabilities and high burst rates are more suitable
- Example: Jupiter with TUM telescope using the Olympus E-M5 Mark II:
  - 150 images at f/20



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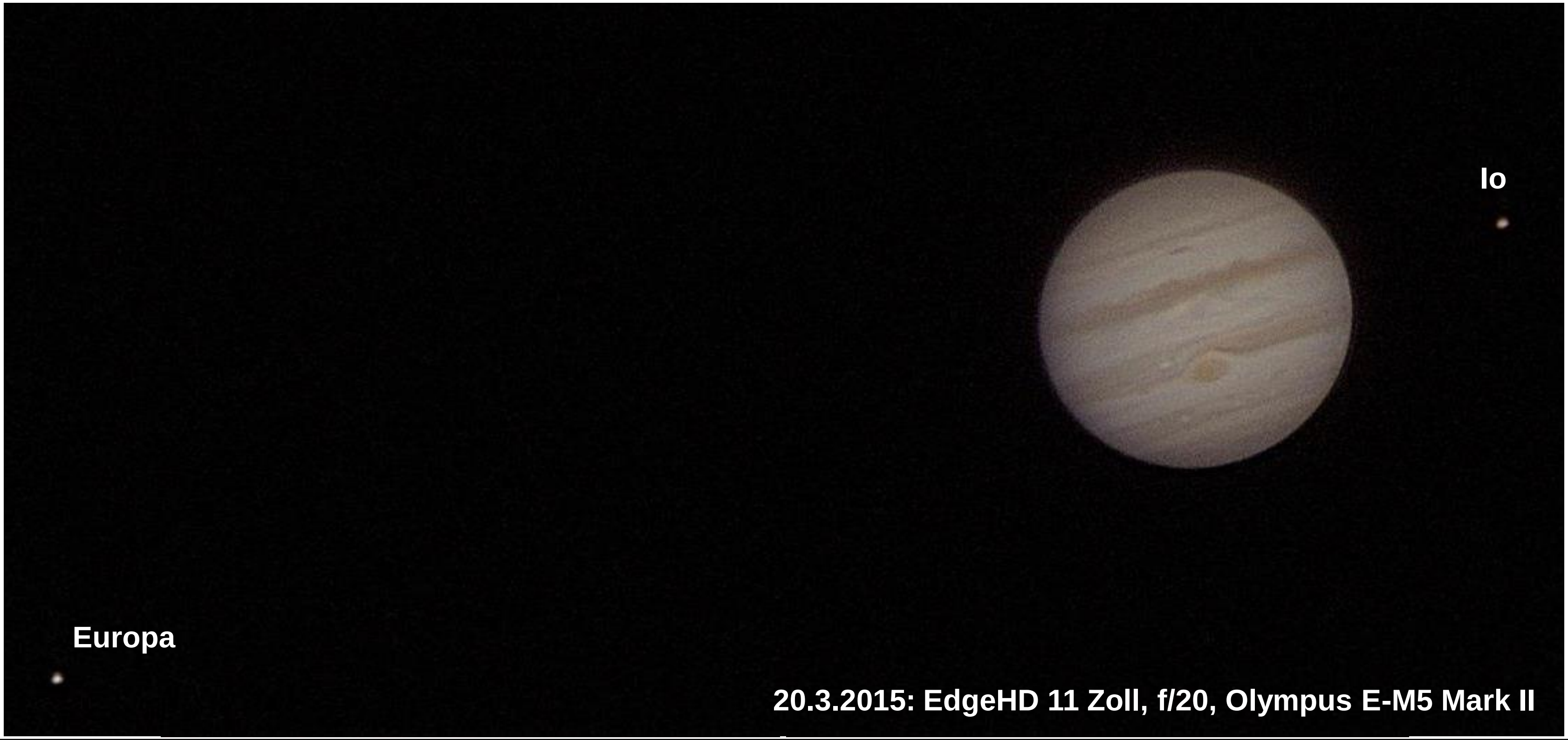
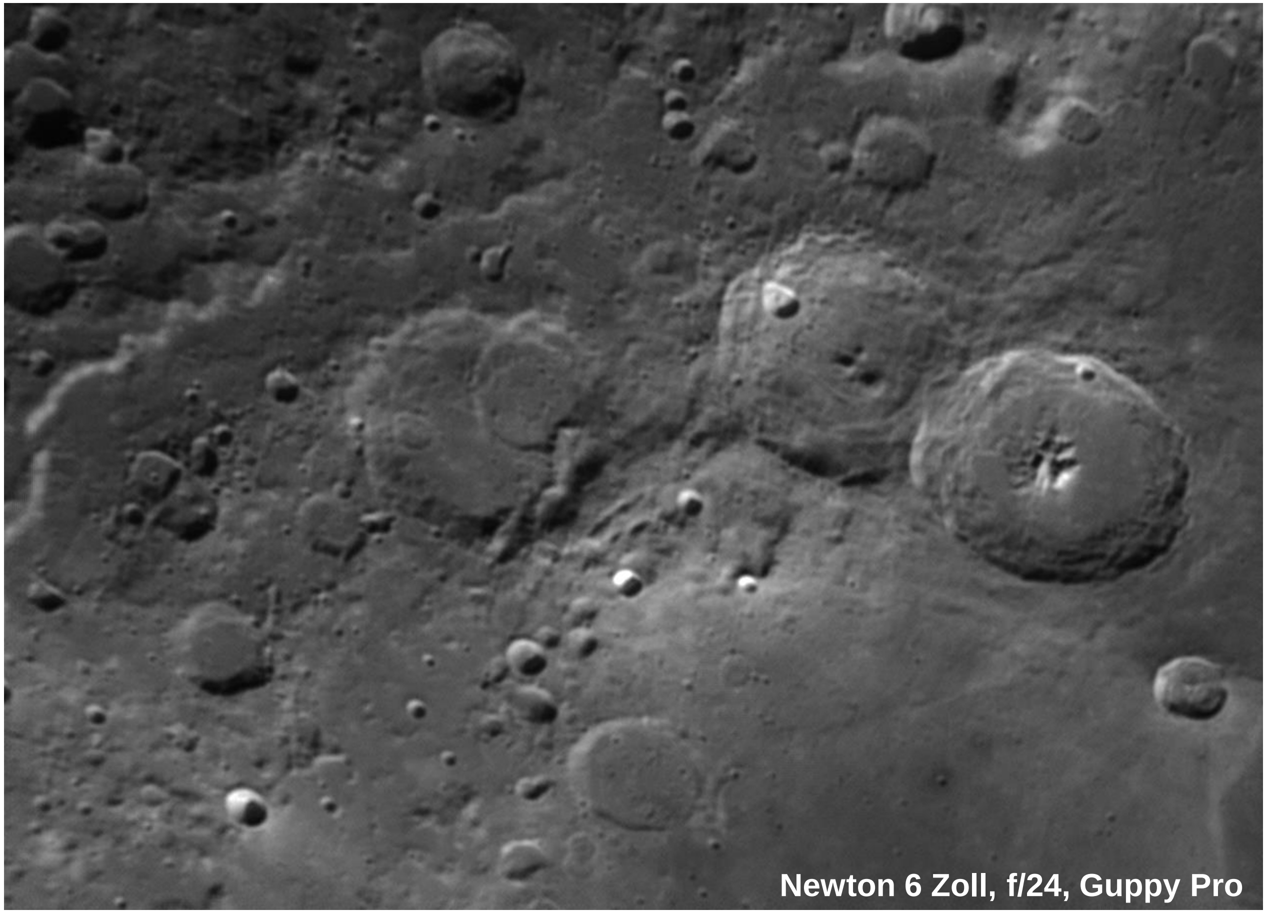


7.6 Image processing using „Lucky Imaging“

- Free software Registax 6: http://www.astronomie.be/registax/index.html
- Example for the moon surface: crater Theophilus



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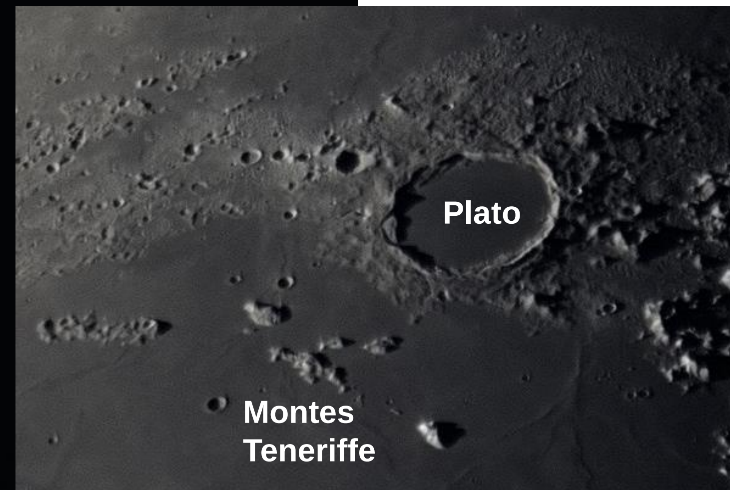
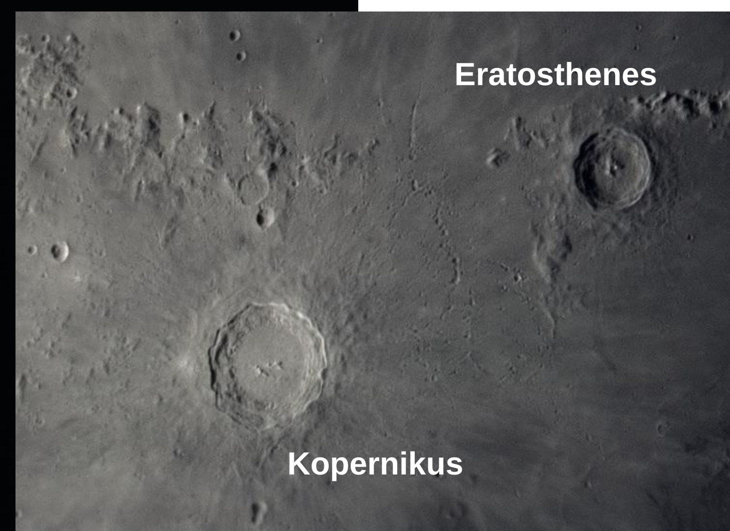


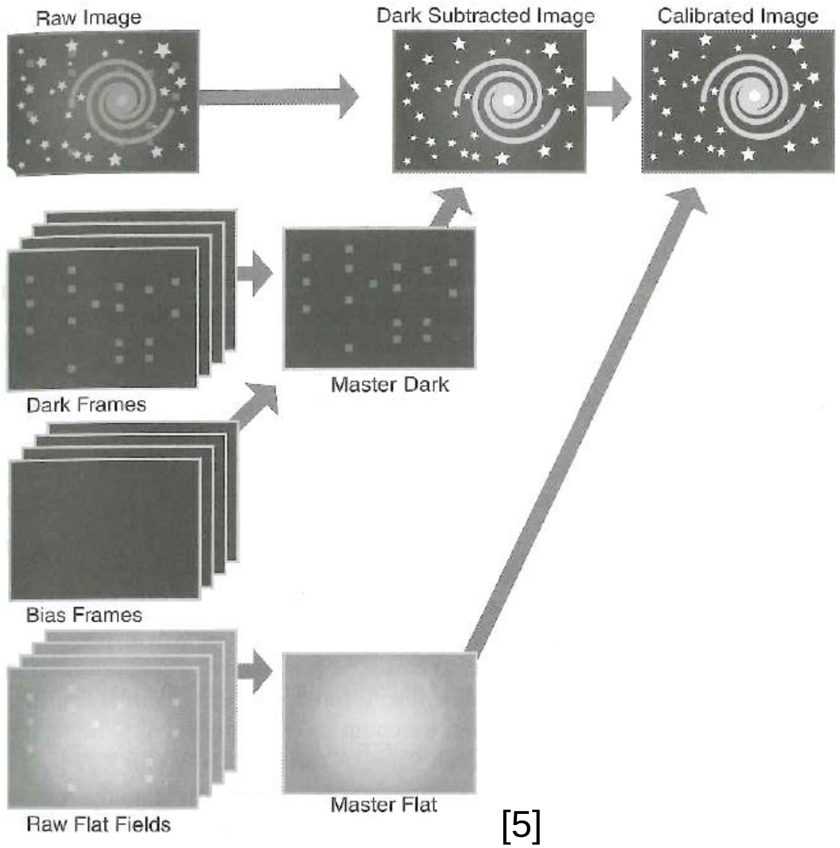


7.8.2015: EdgeHD 11 Zoll, f/7, Olympus E-M5 Mark II

7.7 Processing of Deep-Sky Images

Scheme of data reduction for astronomical imaging

- Professional astronomy: reconstruct the photon flux coming from an object
- Amateur astronomy: deal with noise and vignetting to get clean material for a nice image

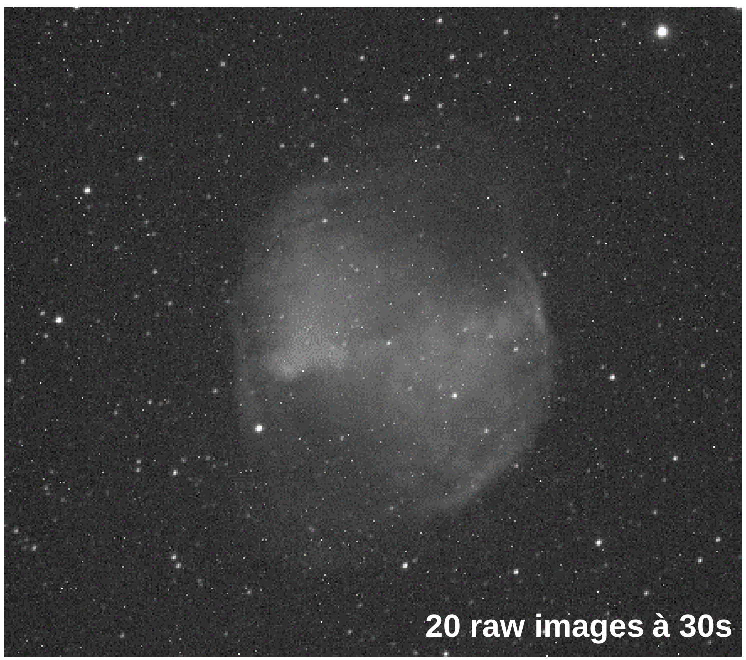


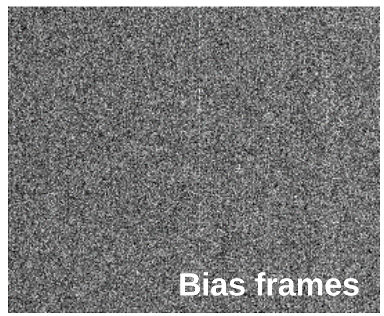
[5]

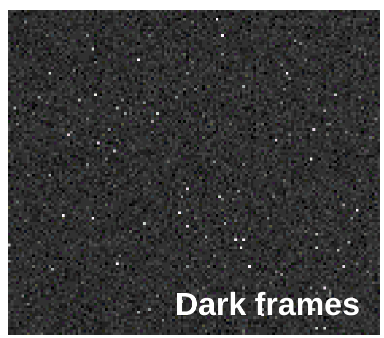
- **Raw image:** image(s) from the camera
- **Dark frames:** images without light (e.g. shutter closed) having the same exposure time as the raw → output is thermally induced noise. Rule of thumb: at least 5x the number of raw images
- **Bias frames:** images without light with shortest integration time available → capture the systematic bias and the read-out noise of the sensor
- **Flat fields:** images from evenly illuminated surface → brightness distribution of the whole imaging train (tube, correctors, filters, dust specks …), received by the sensor → normalize the image output

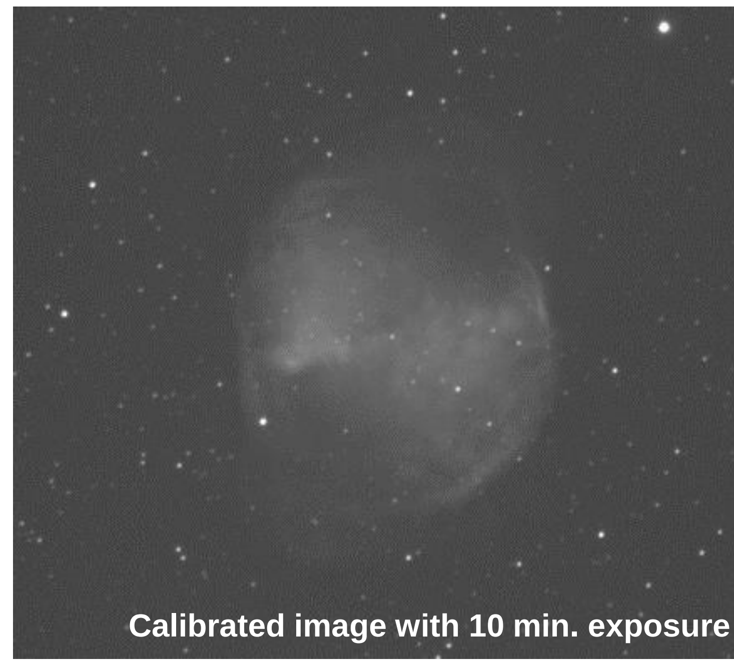
7.7 Processing of Deep-Sky Images

- Example: Messier 27 Dumbbell nebula
- Software:
  - DeepSkyStacker: http://deepskystacker.free.fr
  - Fitswork: http://www.fitswork.de/software/


20 raw images à 30s


Bias frames


Dark frames

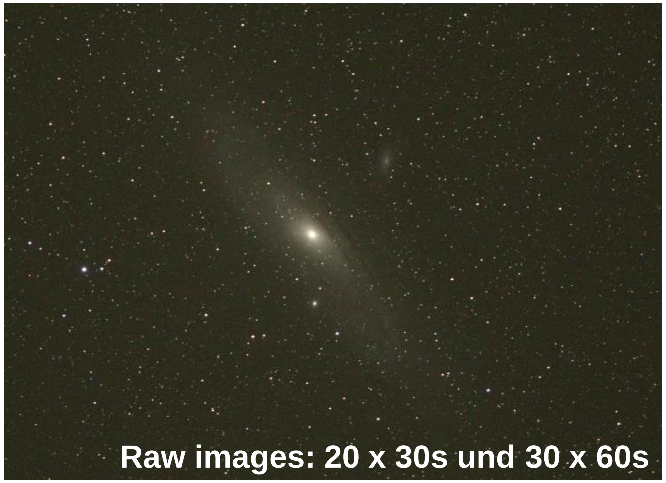

Calibrated image with 10 min. exposure

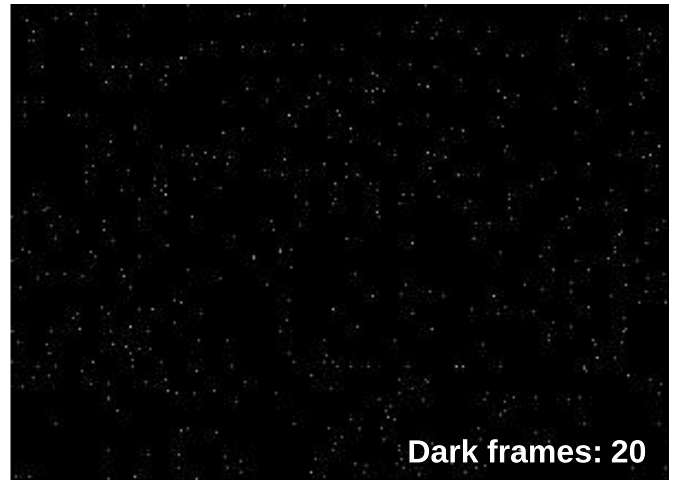
7.7 Processing of Deep-Sky Images

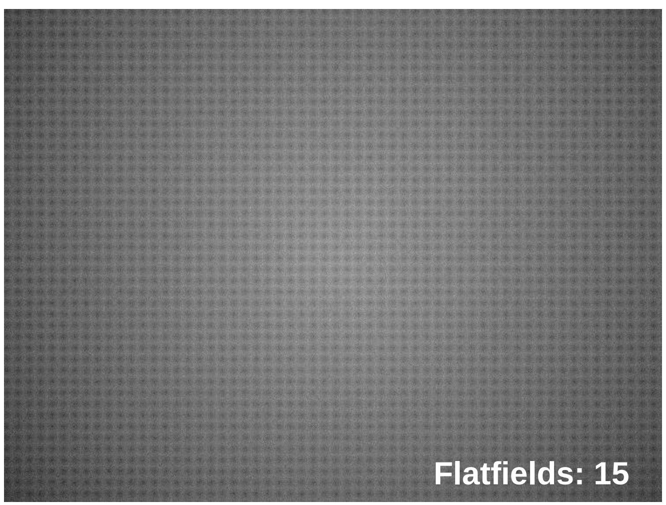
- Example: Messier 27 Dumbbell nebula

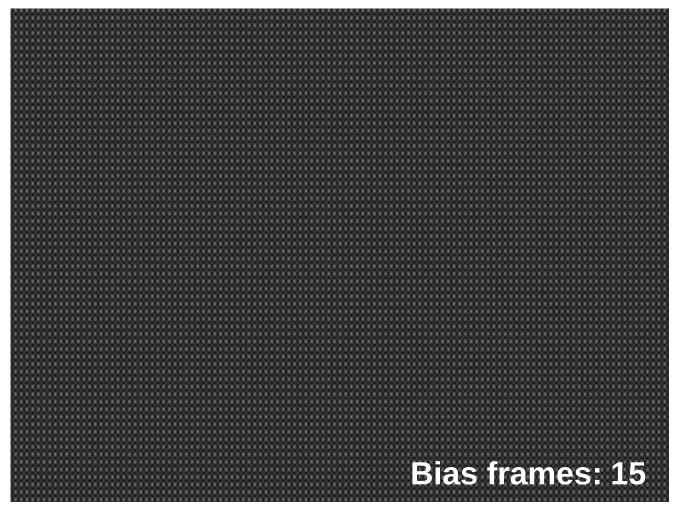
7.7 Processing of Deep-Sky Images

- Example: Messier 31 Andromeda



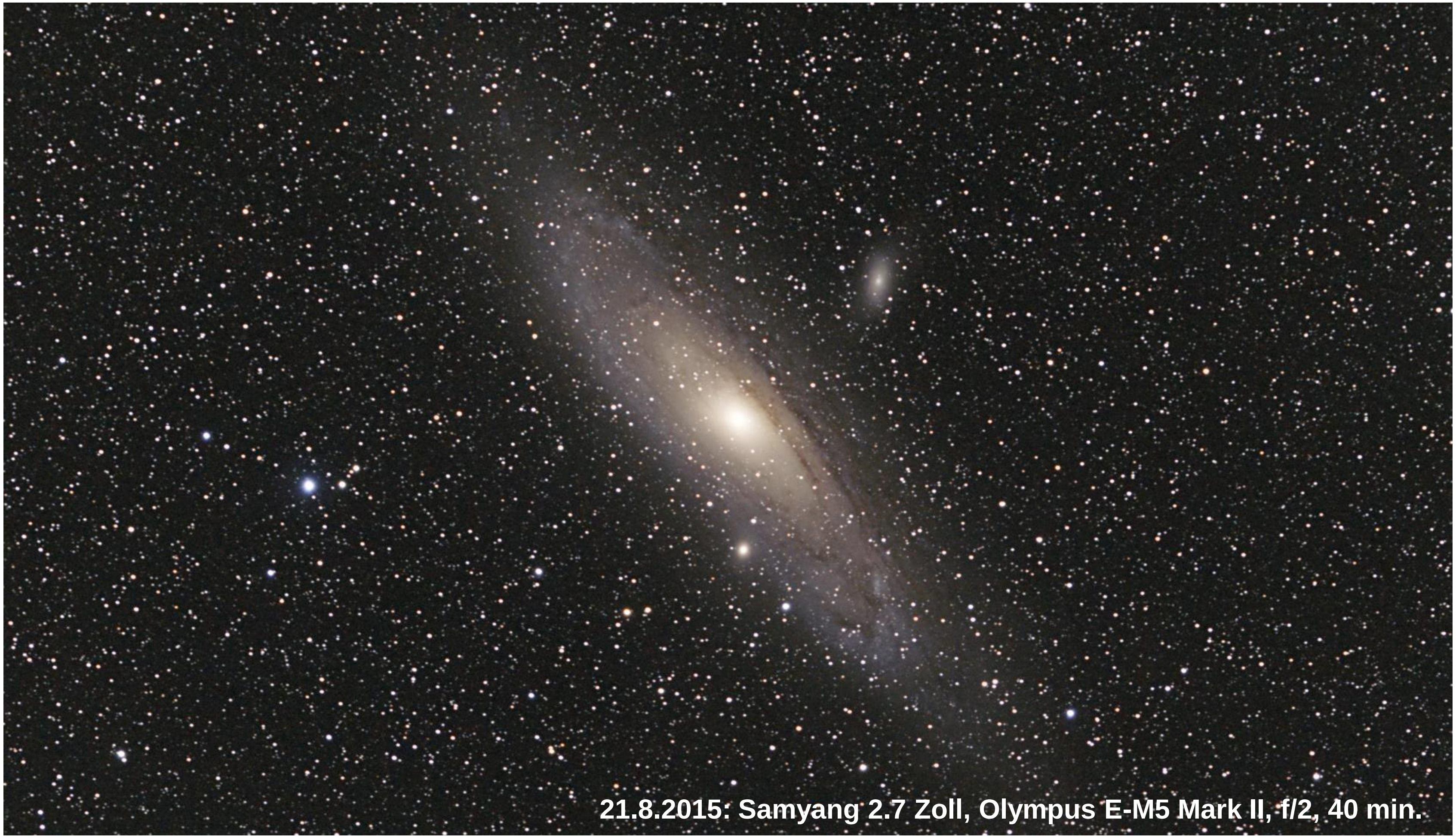






7.7 Processing of Deep-Sky Images

- Example: Messier 31 Andromeda



7.8 Sources

- Richard Berry & James Burnell – *The Handbook of Astronomical Image Processing*, Willmann-Bell, Inc., Richmond, Virginia, USA, 2nd Printing, 2001
- Celestron/Baader Planetarium – Das Celestron EdgeHD Teleskop, Web: http://www.celestron-deutschland.de/brands.php?BrandID=96

7.9 Sources Figures

- [1] Wikimedia Commons, free media repository
- [2] Celestron/Baader Planetarium – Das Celestron EdgeHD Teleskop, Web: http://www.celestron-deutschland.de/brands.php?BrandID=96
- [3] Allied Vision Techonologies – Guppy PRO F-031, Web: http://www.alliedvisiontec.com/
- [4] Finger Lakes Instrumentation – MicroLine ML8300M, Web: http://www.fli-cam.com/microline/index.html
- [5] Richard Berry & James Burnell – *The Handbook of Astronomical Image Processing*, Willmann-Bell, Inc., Richmond, Virginia, USA, 2nd Printing, 2001