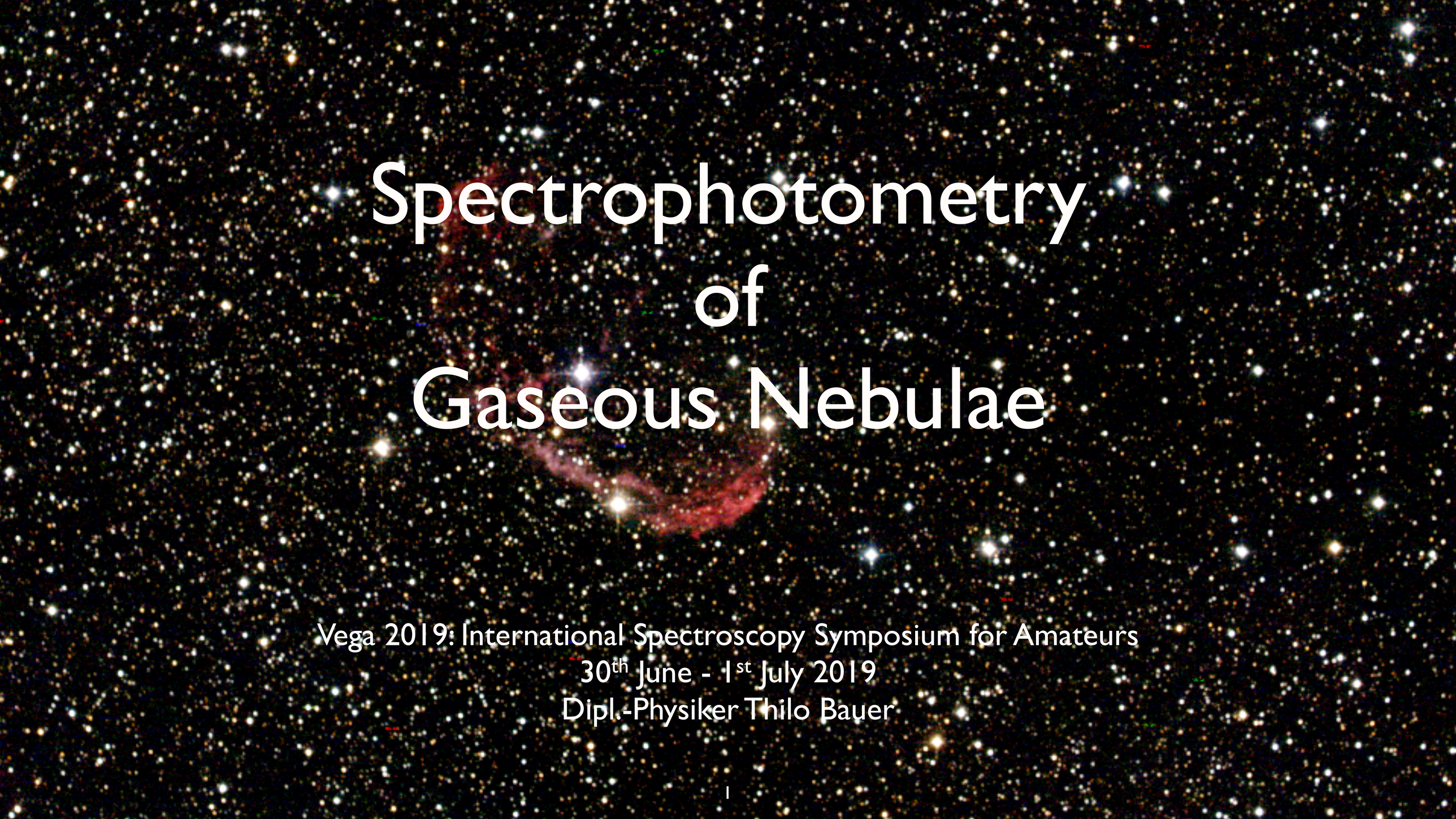


Spectrophotometry of Gaseous Nebulae

Vega 2019: International Spectroscopy Symposium for Amateurs
30th June - 1st July 2019
Dipl.-Physiker Thilo Bauer

Content

- Introduction
- Types of nebula
- Physical properties of the Nebulae
- The project

Introduction

Curriculum vitae

Professional life

- 1985-1989: Physics, Friedrich-Alexander University Erlangen-Nürnberg
- 1989-1991; Max-Planck Institute for Radio Astronomy, MPIfR Bonn
- Thesis (1991): *Photon limited speckle imaging of gravitationally lensed quasars*
- 1992-1997: Observatory Hoher List, University of Bonn
- 1989/1990/1994: Guest observer at ESO
- 1996: Bauer, T.; Weghorn, H.; Grebel, E. K.; Bomans, D. *The young star cluster R 64 (HD 32228) in the LMC observed with a new high-resolution CCD imaging system*
- 1997-2014: Self-employed in information technology
- 2007-… Private professor (information technology)
- 2014-… Schenker AG (Deutsche Bahn)

Private life

1997-2007: No scientific work, no astronomy at all.

2007-… Independent researcher

- Informatics & information technology
- High-resolution imaging, super resolution
- Astronomy
- Fluorescence microscopy, biological applications

2010: ***Outstanding Paper Award***

- Bauer, Thilo. Efficient Binning of Photographs. Proceedings of the IADIS International Conference, Informatics 2010, 26 - 28 July 2010, Freiburg, Germany, p. 19-25. edited by H. Weghorn, J. Roth and P. Isaias. ISBN: 978-972-8939-19-9

Observatory Hoher List

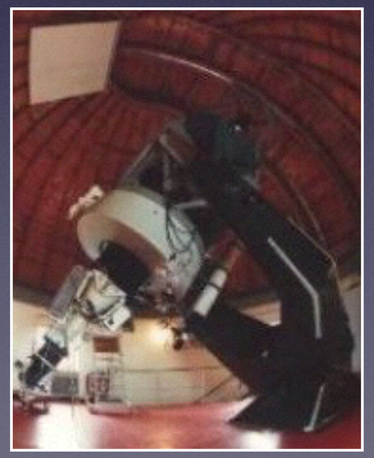
My life with the large telescopes at La Silla, Chile and the 1m Cassegrain at the Hoher List Observatory.

At the Hoher List Observatory we had

- Focal Reducer
- Astromed CCD
- Interference Filters
- Grating prisms
- Polarizers

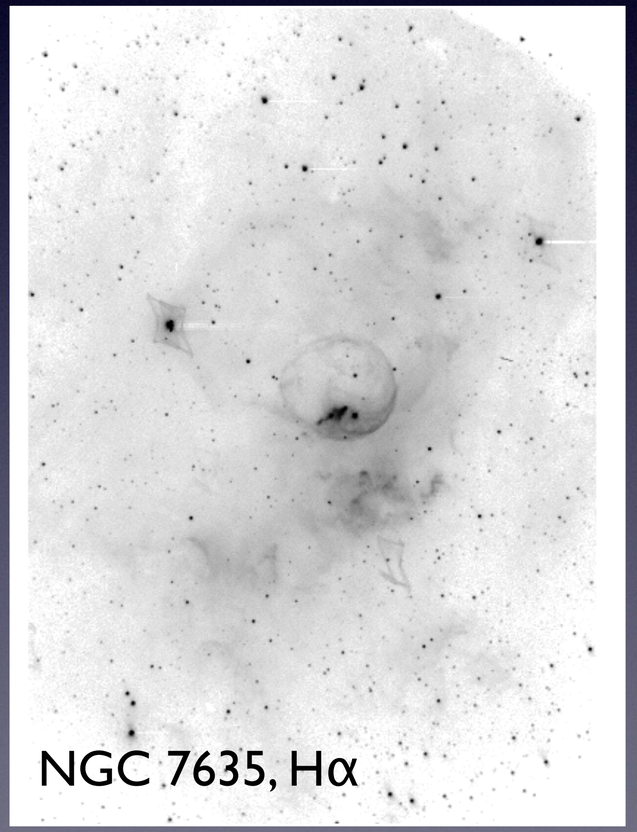
My contribution

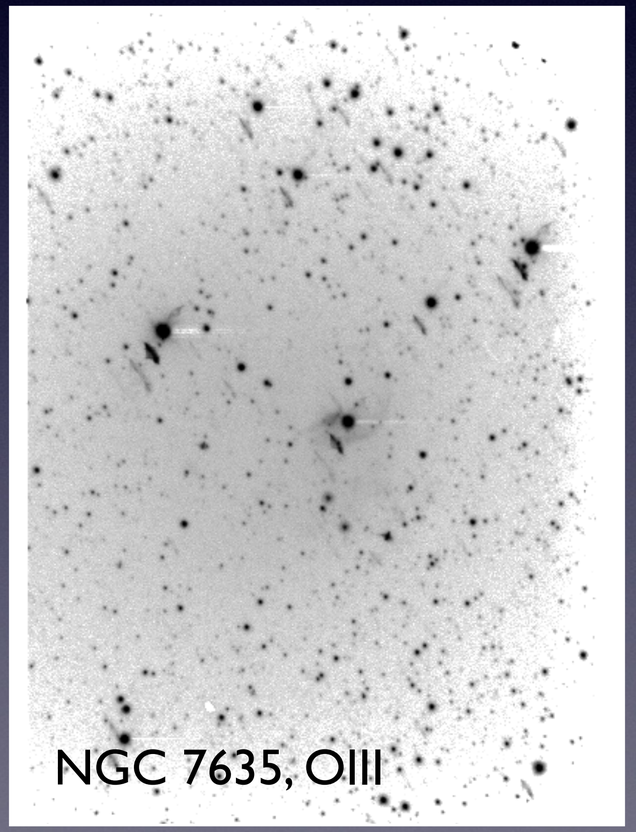
- Development of the REVRAVEL
- Analysis of line profile fits with high accuracy (~0.01 pix)

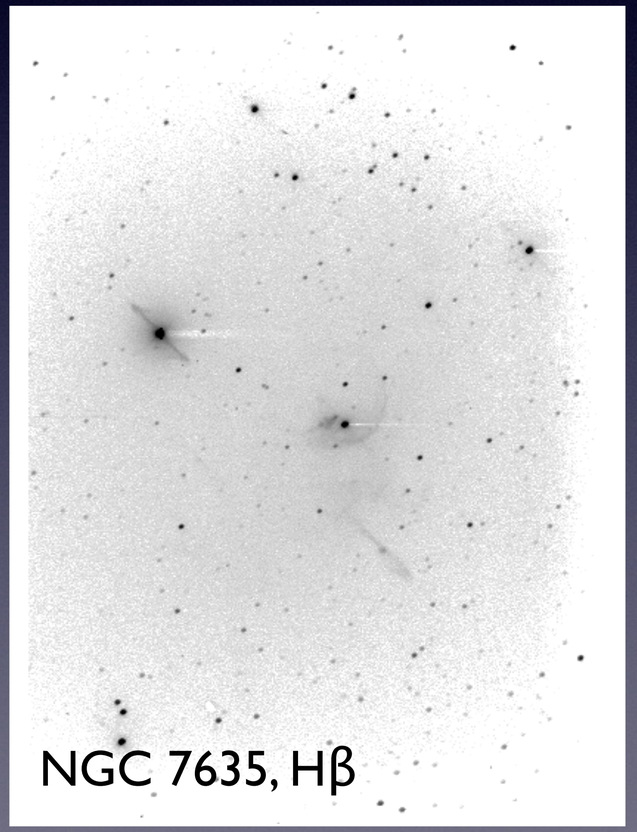


Spectrophotometry of emission nebula

CCDs had some problems in the blue spectrum:
Exposure time typically increased by a factor of four.


NGC 7635, Hα

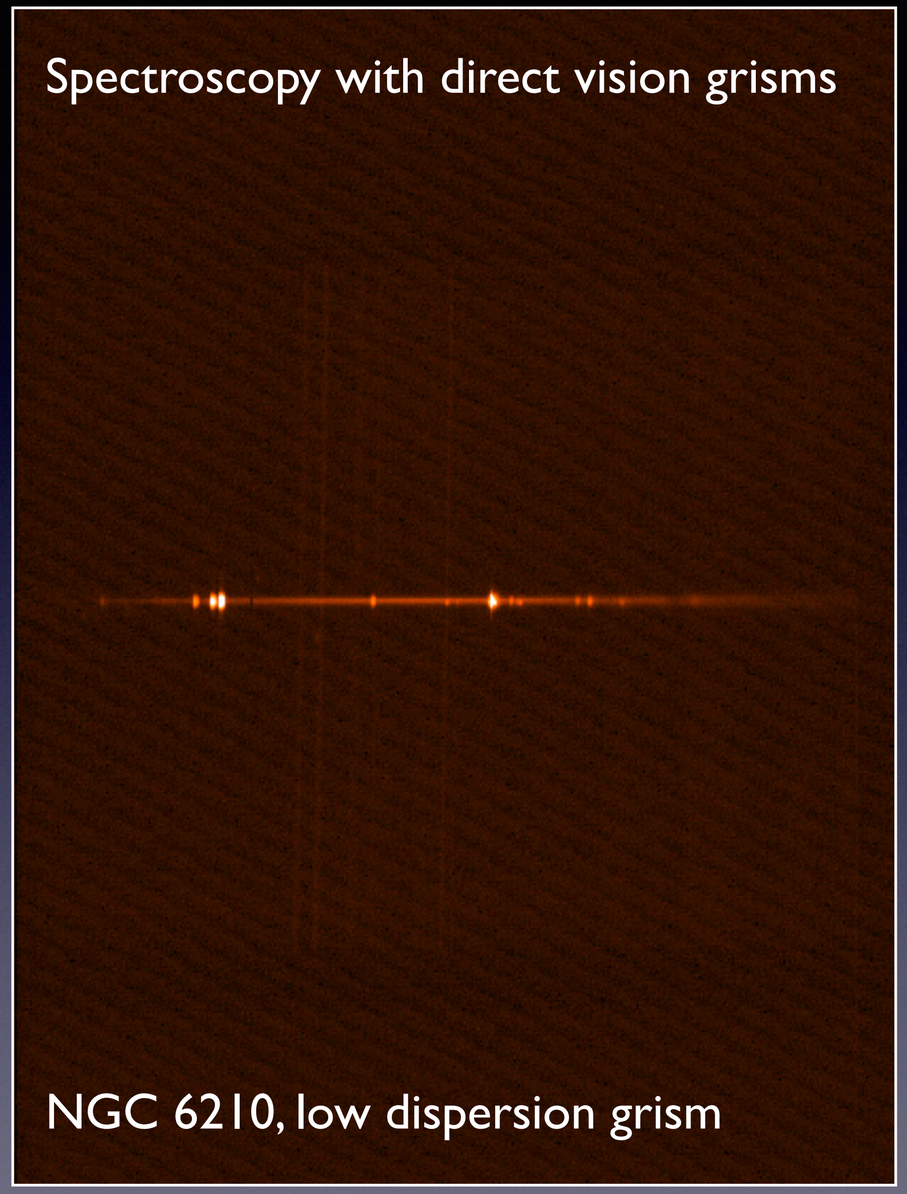

NGC 7635, OIII


NGC 7635, Hβ

Observatory Hoher List

The color differences of the images resulted from

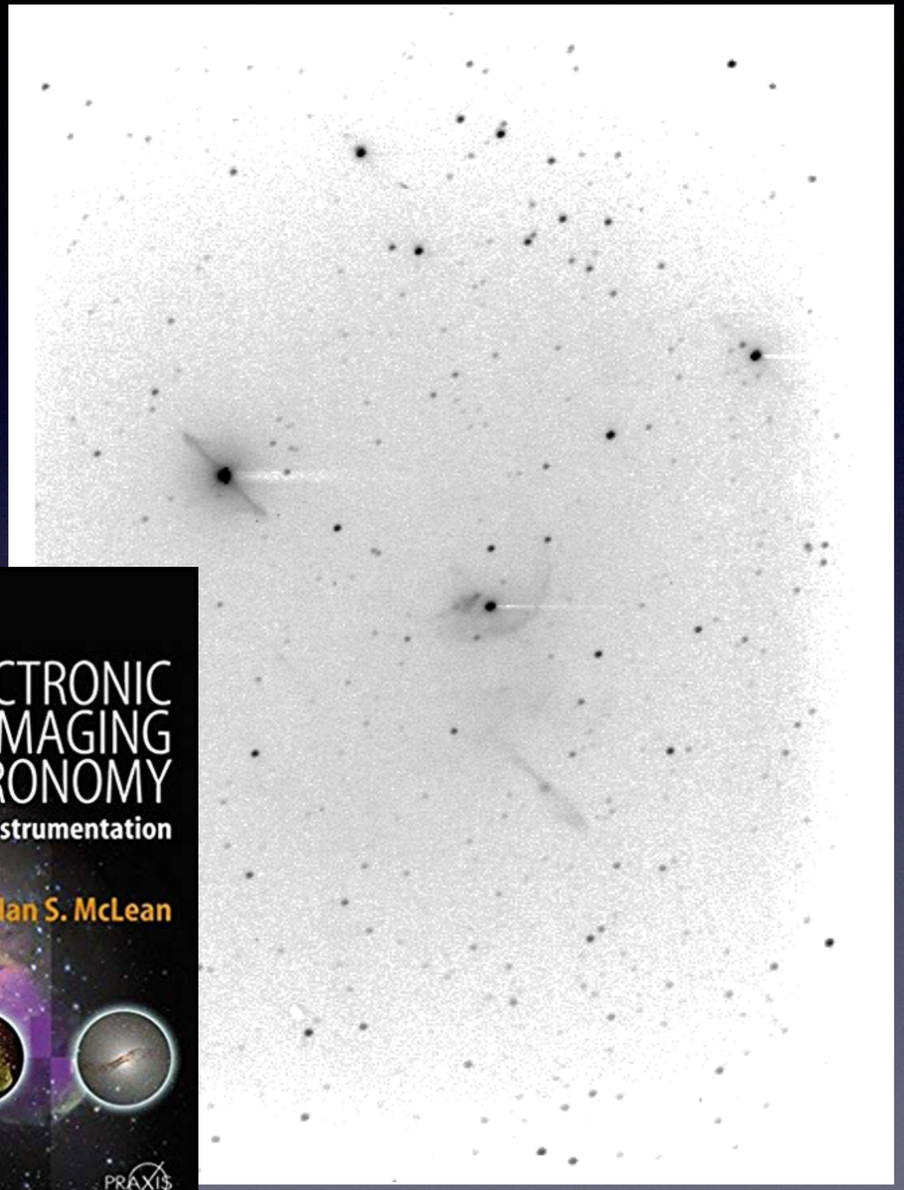
- Abundance of elements
- Density of the gas
- Temperature of the gas
- Interstellar reddening
- Atmospheric transmission
- Response of the imaging sensor

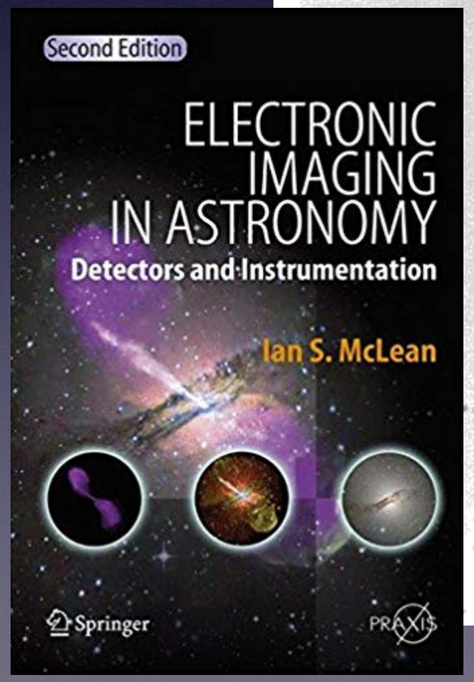


Observatory Hoher List

Disadvantage of a CCD device

- Prone to image defects
- Blooming
- Poor sensitivity in the blue
- Slow readout, otherwise noisy
- Read-out artifacts, asymmetric profiles
- Practical noise properties did not reflect laboratory measurements of the manufacturers



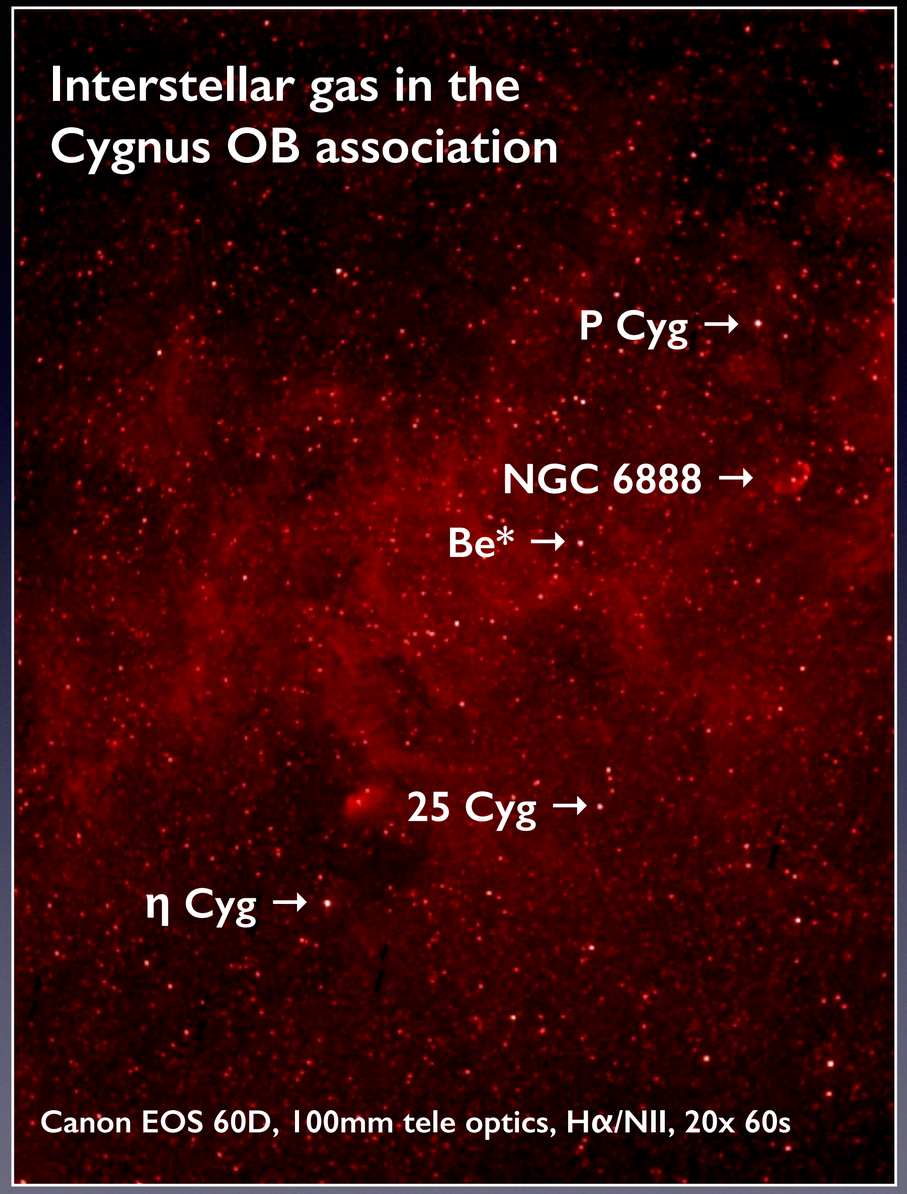


Types of nebulae

Diffuse nebulae

Diffuse nebulae or HII regions are regions of interstellar gas, in which the exciting star(s) are typically of spectral type O or B, in certain cases peculiar types, like Wolf-Rayet stars or white dwarfs.

Only these spectral types of stars emit sufficient energy in the UV light to excite the interstellar gas in a way, that light of the gas gets emitted by exited states of the neutral atoms on a large scale.



Diffuse nebulae

In certain cases peculiar O stars like WR stars are exciting the gas.

Such stars also have interesting properties, as they emit a shell of gas, thus having emission lines.

Canon EOS 60D, 8“ Cassegrain, 20x 60s

Diffuse nebulae

There are not only single O or B stars exciting the gas, but also associations of young star clusters.

Planetary nebula

Planetary nebula are isolated nebulae, often, but not necessarily possessing a fair degree of symmetry.

Planetary nebula today are defined as a gas nebula which contains a central star.

- ~~Supernova remnant~~
- Ejected shell of a star < 8 $M_\odot$
- Shockwave(s) in red giant AGB phase
- Sometimes multiple shells are found

White dwarfs as hot central stars are found to excite the planetary nebula.

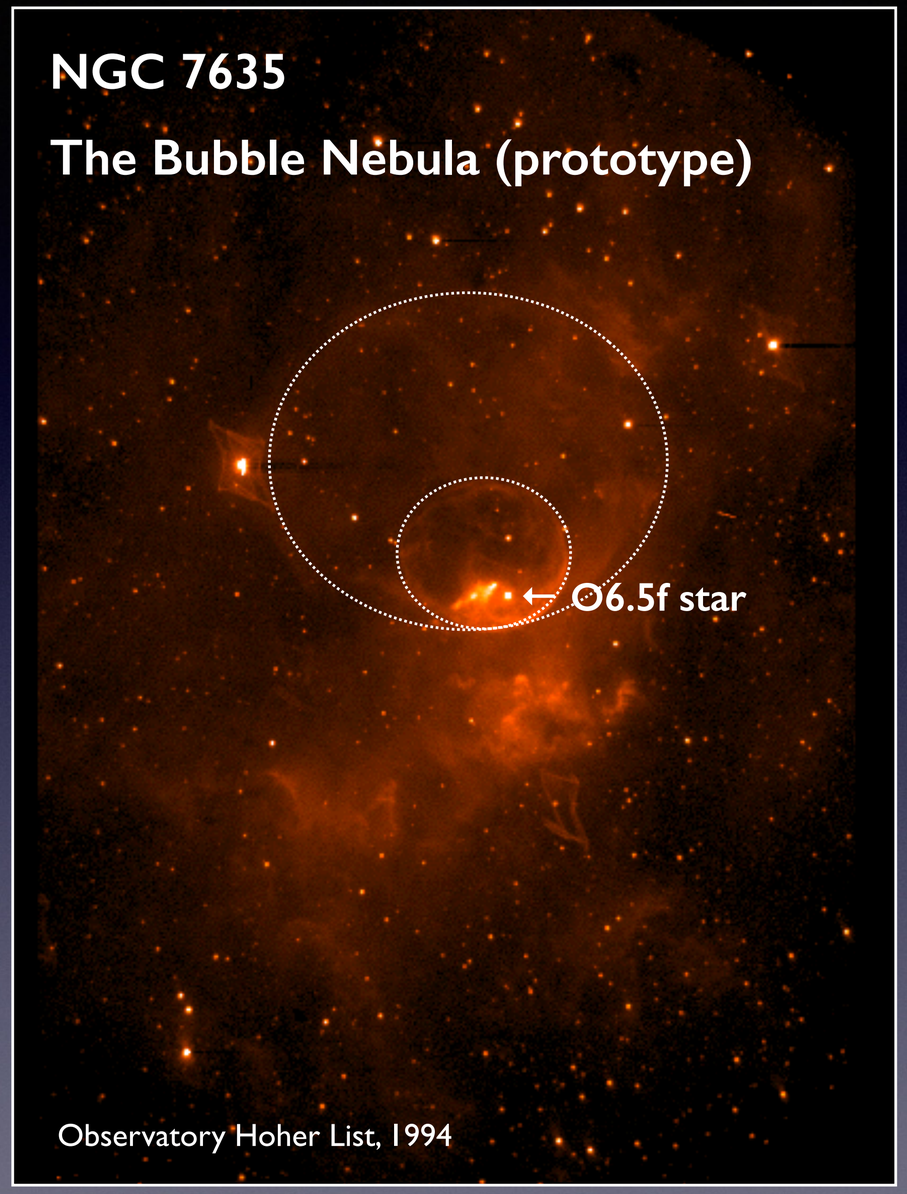
White dwarfs are typically found with planetary nebulae as a remnant of the former star.

Wind blown bubbles

Bubbles in the sky sometimes are falsely referred as „planetary nebula“ until today.

NGC 7635, the famous prototype of a bubble nebula was long discussed as a planetary nebula, but the central star was missed. Extensive research has been done also in the infrared to find the missing central star.

In the field of NGC 7635 there exist a few bubbles blown over time, some of them barely visible. These have been confirmed as wind-blown, expanding shells by spectroscopic observations.



Christopoulou, P. E., et al. "The kinematics of an ionized shell, NGC 7635, in the S162 complex." Astronomy and Astrophysics 295 (1995): 509-516.

Physical properties of nebula

Photoionization & Recombination

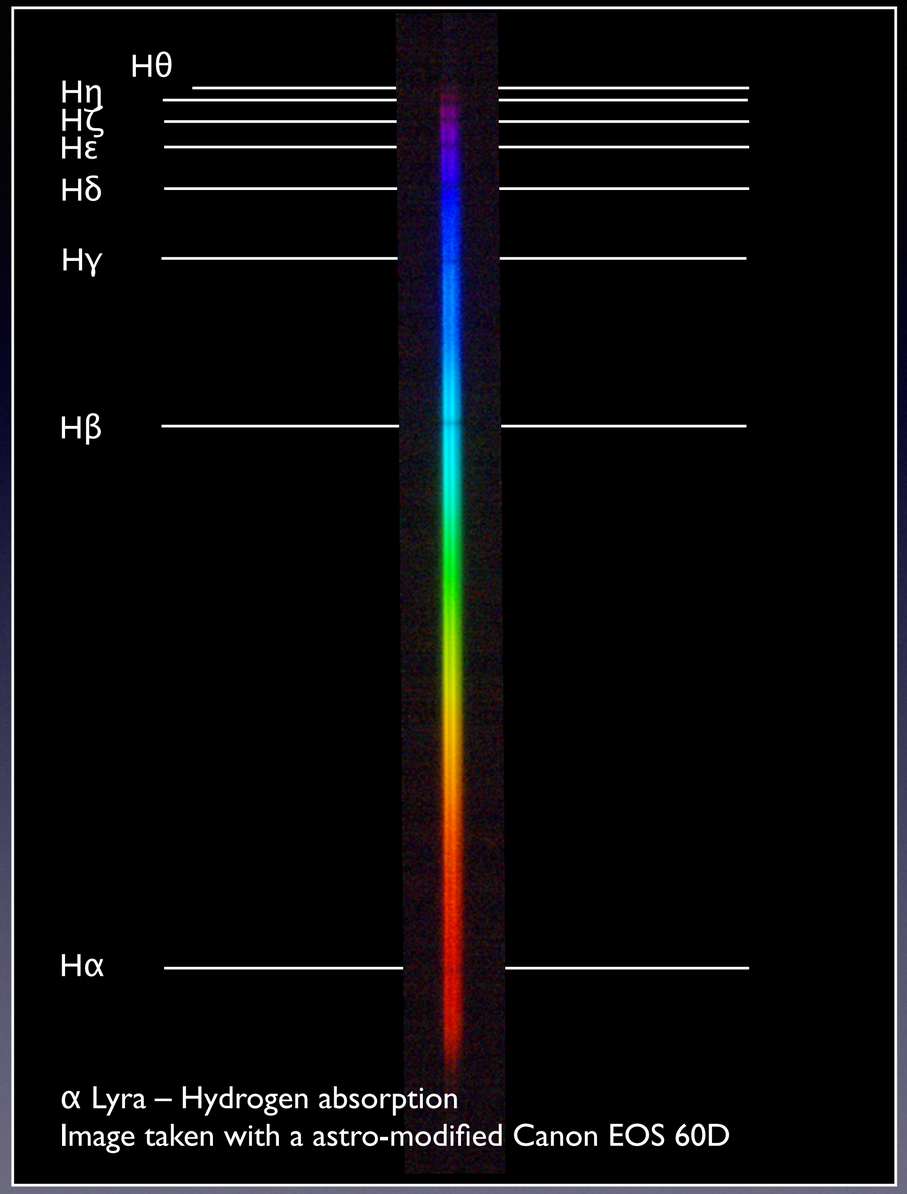
Absorption lines of stars

Dark lines occur in stellar spectra of the emitted light caused by absorption of light in the line of sight.

Emitted light is absorbed by atoms in the stellar atmosphere, then scattered from here.

Because of the scattering a broader dark line occurs at wavelengths, that reflect the absorbed and scattered light energies.

Profiles and widths of the stellar lines highly depend on temperature, atmospheric pressure or rotation of the stellar atmosphere.



α Lyra – Hydrogen absorption
Image taken with a astro-modified Canon EOS 60D

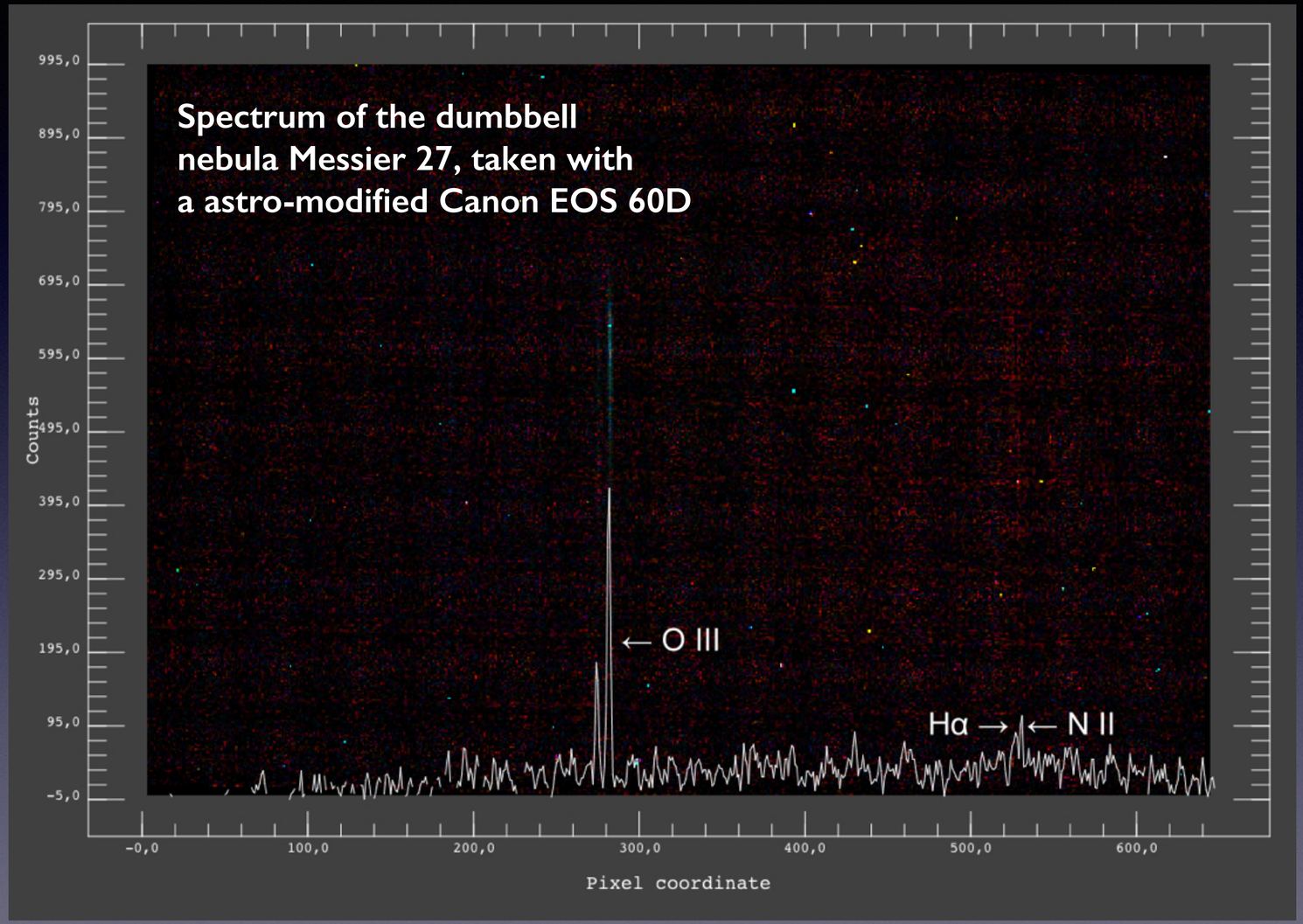
Photoionization & Recombination

Emission lines of nebula

Prominent emission lines are found.

The spectral lines indicate the chemical elements in abundance.

Line ratios depend on other physical parameters.



Photoionization Equilibrium

Emission nebulae seen in the optical result from the photoionization of a diffuse gas cloud by ultraviolett photons.

Typically hot O and B stars emit UV radiation to ionize the gas.

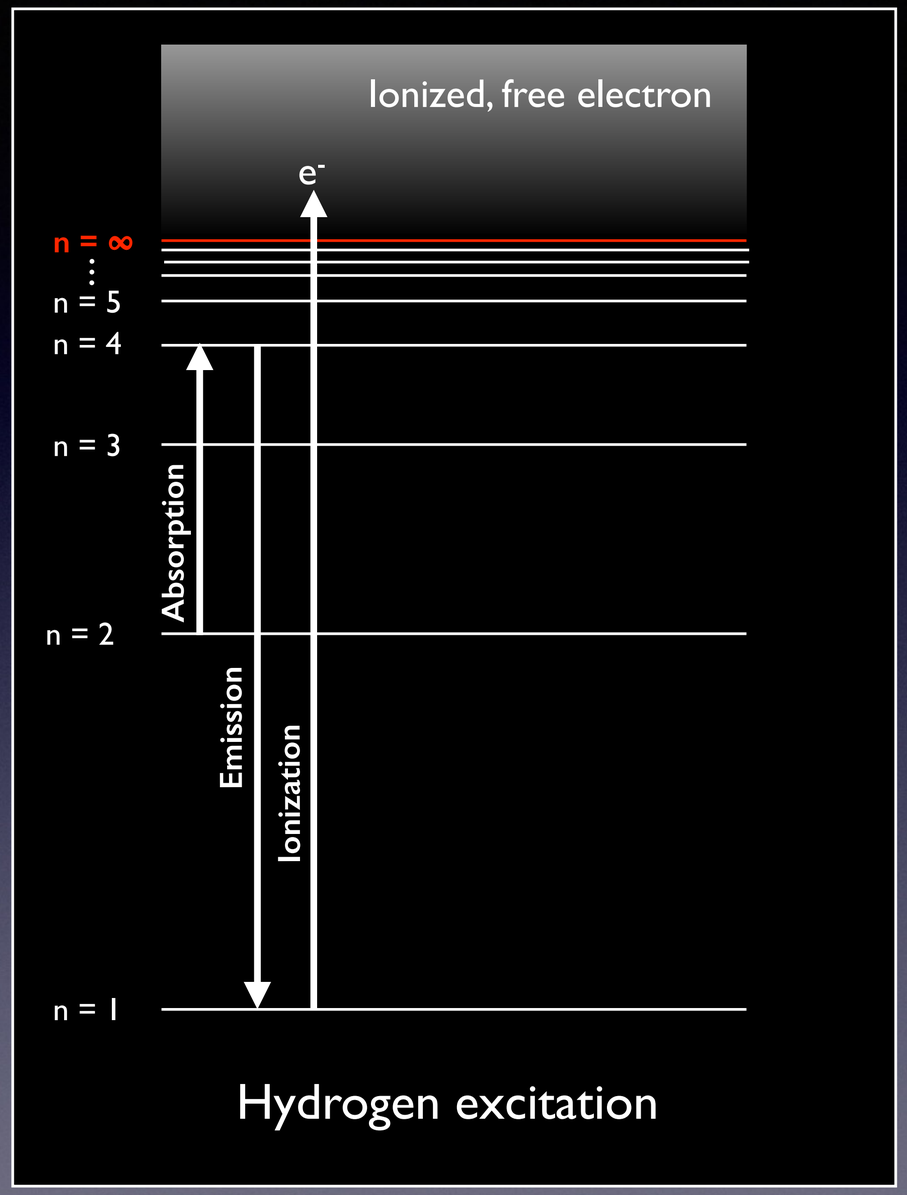
NGC 1893 + SH 2-236 (IC 410)
A young cluster of hot stars embedded in a H-II region SH 2-236.

Photoionization & Recombination

Absorption: Certain discrete energy levels excite the electron to a higher energy level.

Emission: The electron spontaneously moves back to ground state and emits the absorbed energy.

Ionization: If added energy is larger than a certain level, the electron is freed and the atom remains ionized.

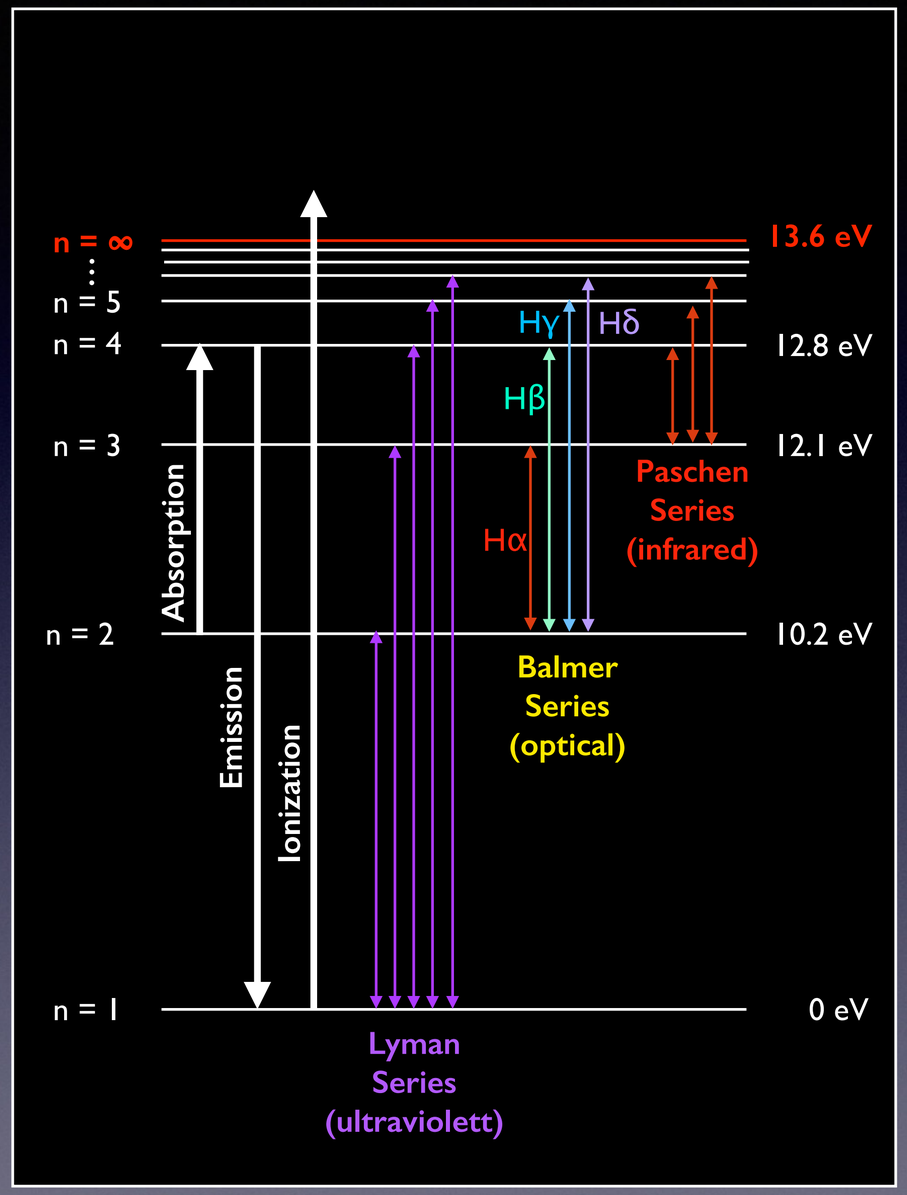


Pure hydrogen nebula

Consider the simple idealized problem of a single star as a source of ionizing photons in a homogenous static cloud of hydrogen H.

Hydrogen gas will show several spectral line series with (theoretically) unlimited number of spectral lines of the excited atom. Only Balmer series is visible in the optical range.

Ionization energy of hydrogen: 13.6 eV.



Strömgren sphere

In the simple model of a cloud of gas, there can be a sphere of **ionized hydrogen H-II** around a hot star of spectral classes O or B.

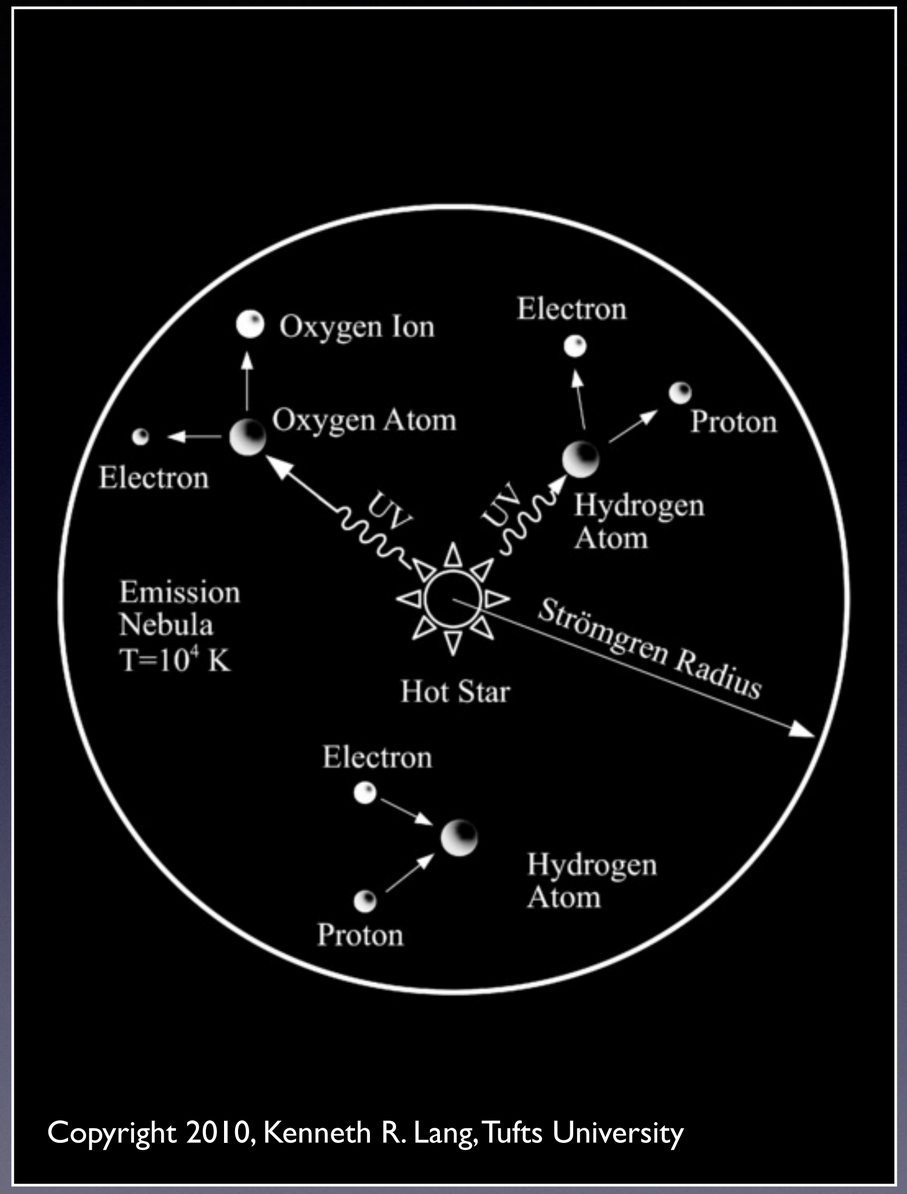
The outer radius r_{limit} where ionization is nearly complete is given by

$$4\pi R^2 \int_{\nu^0}^{\infty} \frac{\pi F_\nu}{h\nu} d\nu = \frac{4\pi}{3} r_{limit}^3 n^2 \alpha_B$$

where

$$4\pi R^2 \pi F_\nu(R) = L_\nu$$

is the luminosity L_ν of the star at frequency ν.
The radius r_{limit} is also called Strömgren radius.

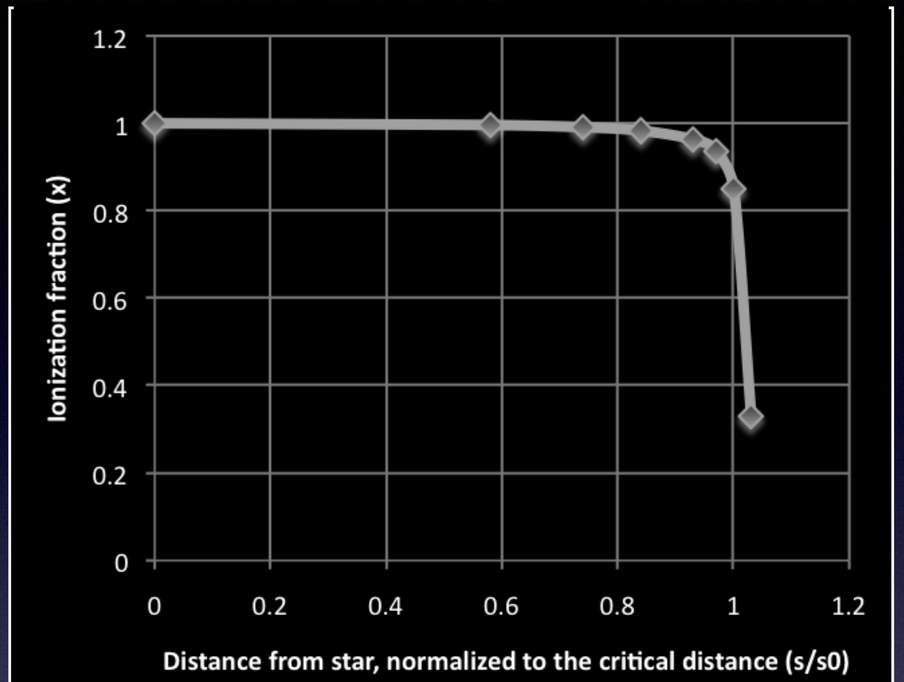


Strömgren sphere

The total number of photons emitted by the star just balances the total number n of recombinations.

Ionization to partial ionization is found up to the Strömgren radius.

Depending on the spectral type of the hot star, the Strömgren radius varies in size.



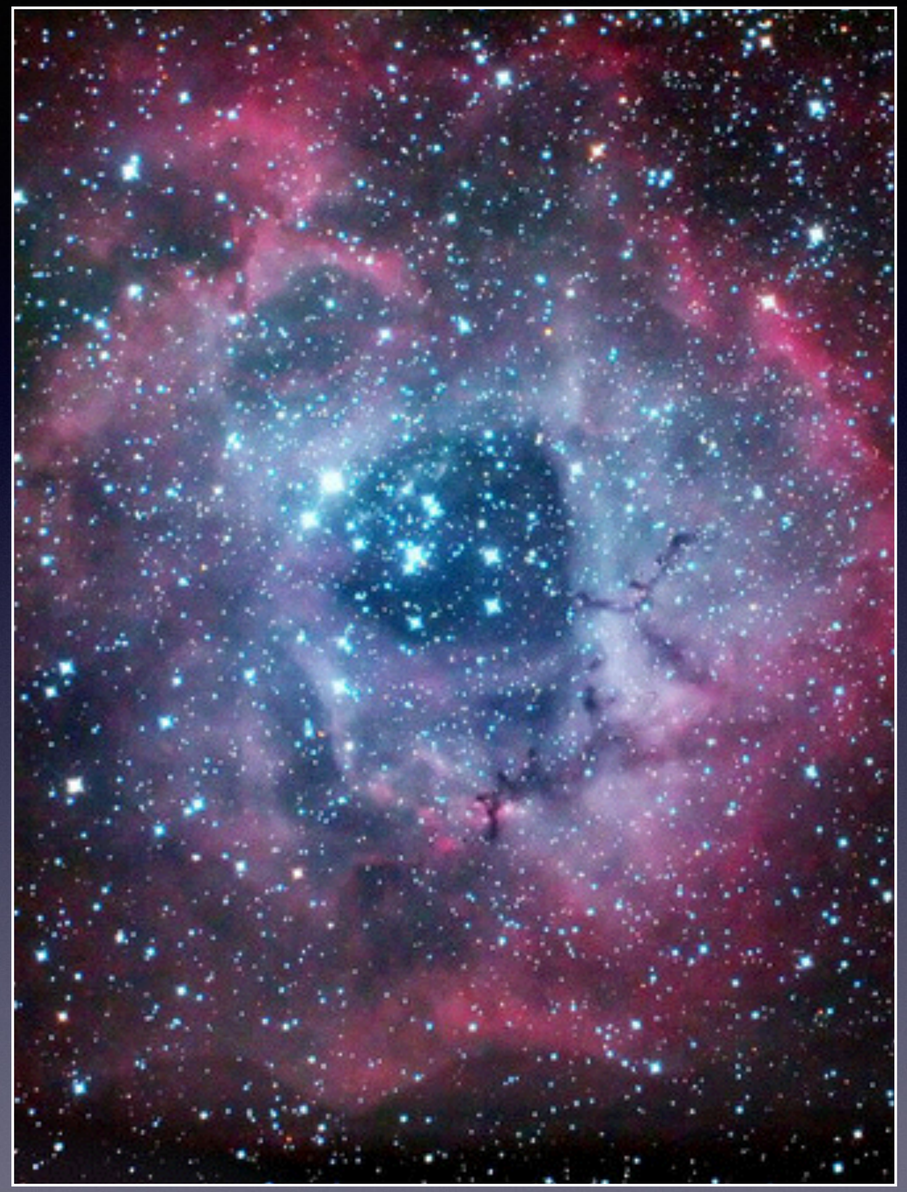
Spectral type	T [K]	r_{limit} [pc]
O3 V	51200	122
O5V	46100	94
O6V	43600	81
O8V	38400	57
B0V	33300	33
B0.5V	32000	27

Strömgren sphere

The theoretical computations of the Strömgren sphere have prominent examples in nature, like the famous **Rosetta nebula**.

Approximately 2500 young stars lie in this star-forming complex.

The massive O-type stars HD 46223 and HD 46150 are primarily responsible for blowing the bubble and ionization of the gas.

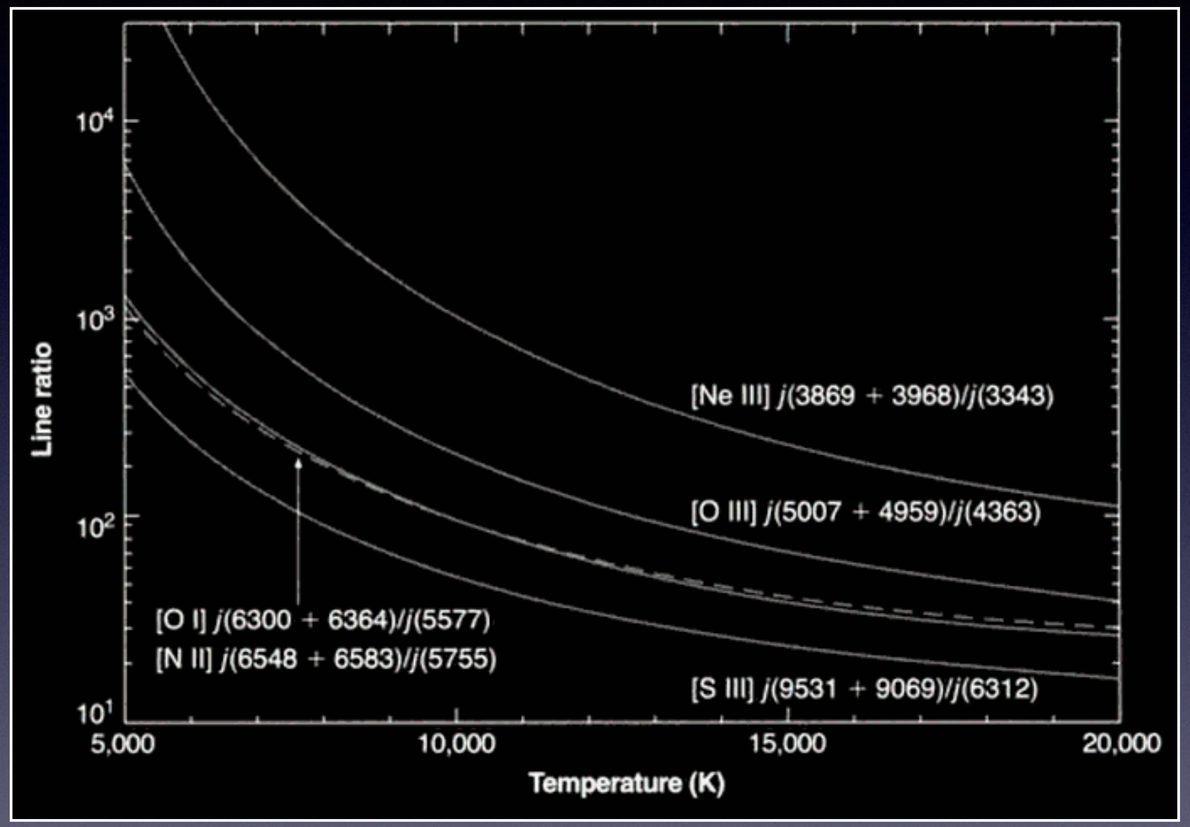


Temperature: Forbidden lines

Temperature of the interstellar gas can be measured using line ratios of forbidden lines.

In the optical range these lines can be used (where available):

- N-II: (λ6548 + λ6583) / λ5755
- O-I: (λ6300 + λ6364) / λ5577
- O-III: (λ5007 + λ4959) / λ4363
- Ne-III: (λ3869 + λ3969) / λ3343

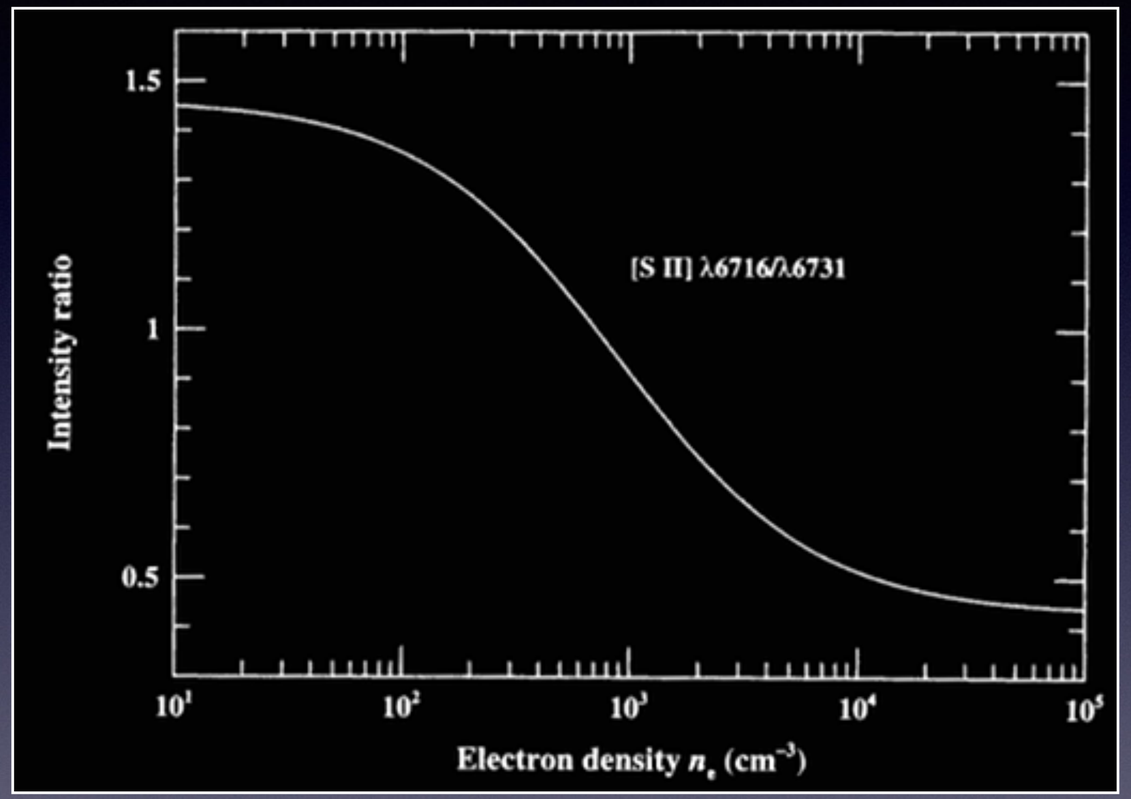


Electron density from line ratios

Density measures are possible using the intensity ratio of spectral lines.

In the optical range these lines can be used (where available):

- O-II: λ3729 / λ3736
- S-II: λ6731 / λ6716



Planetaries as standard candles

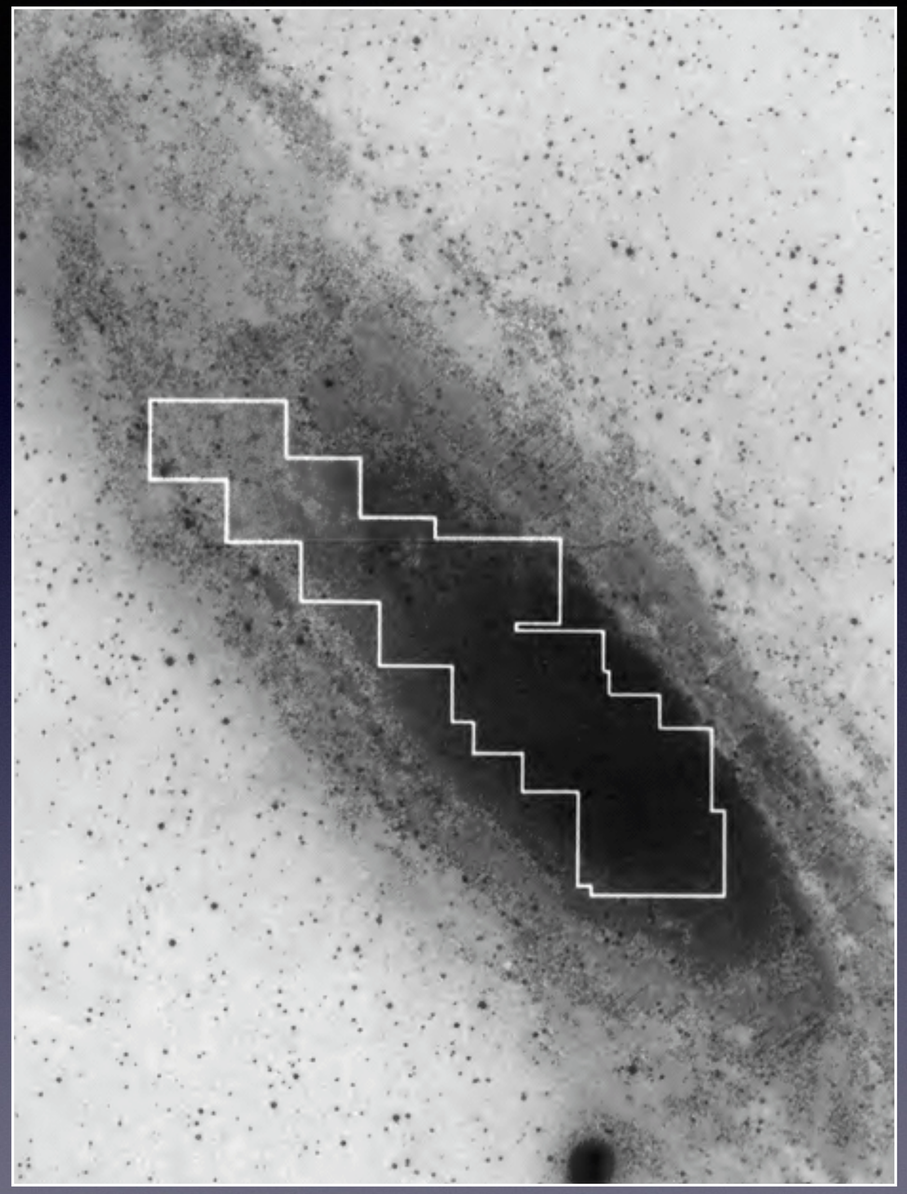
The more far we look into the universe, the more uncertain the distances are.

Before we can discuss the Hubble universe we should figure out distances.

Aside from bright variable stars, like Cepheids, also planetary nebula may be chosen to measure the distance of a galaxy.

An extensive project uses O-III emission of planetaries to estimate distances of galaxies.

Ciardullo, Robin, et al. Planetary nebulae as standard candles. II The calibration in M31 and its companions. The Astrophysical Journal, 1989, 339. Jg., S. 53-69.

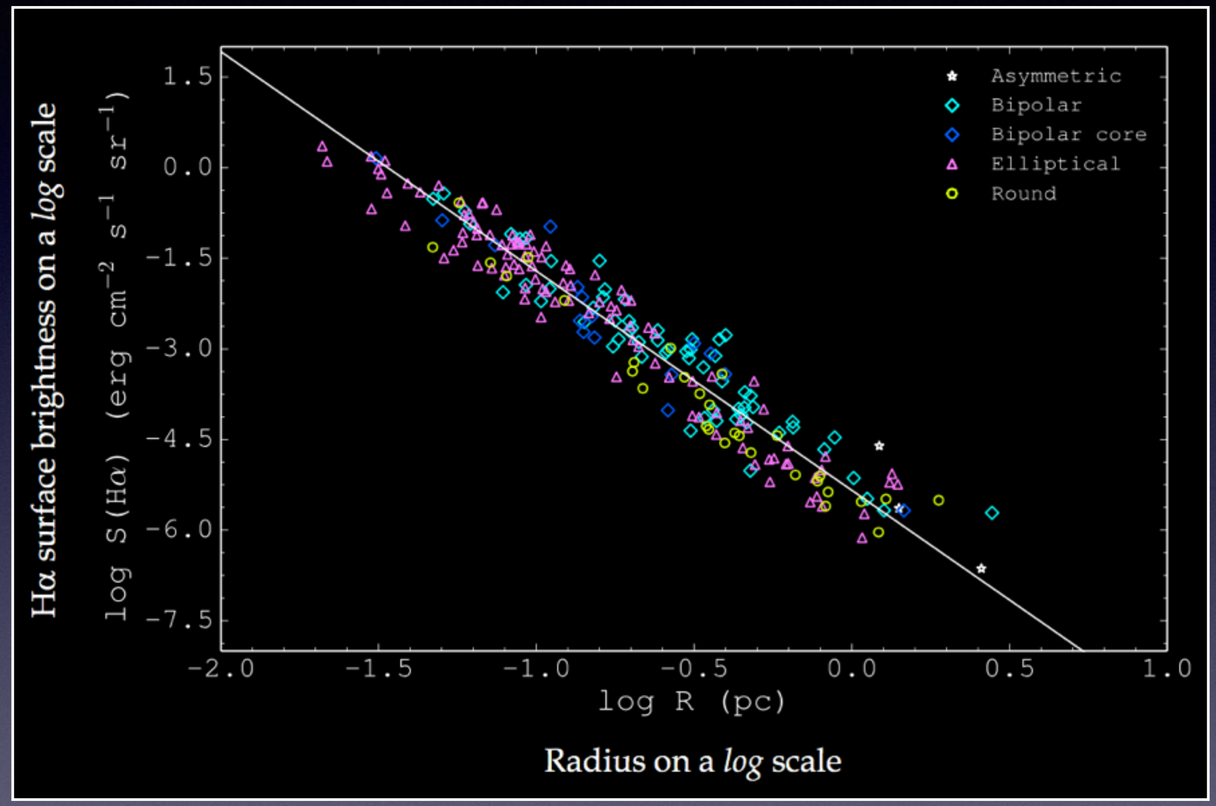


The Distance Problem

- We cannot generate a census without knowing their distances. Most planetary nebulae are fairly remote.
- PNe are not *'standard candles'*, nor *'standard rulers'*.
- Most Galactic planetary nebulae in the Milky Way were too distant for a trigonometric parallax, cf. the recently launched GAIA satellite.
- But PNe do decrease in surface brightness (flux per unit area) as they expand (radius increases).

The Hα S-r relation

- New statistical distance scale developed
- First to measure brightness in Hα emission



Frew D. et al. 2016: Ghostly and beautiful "planetary nebulae" finally get more accurate distances.

About the project

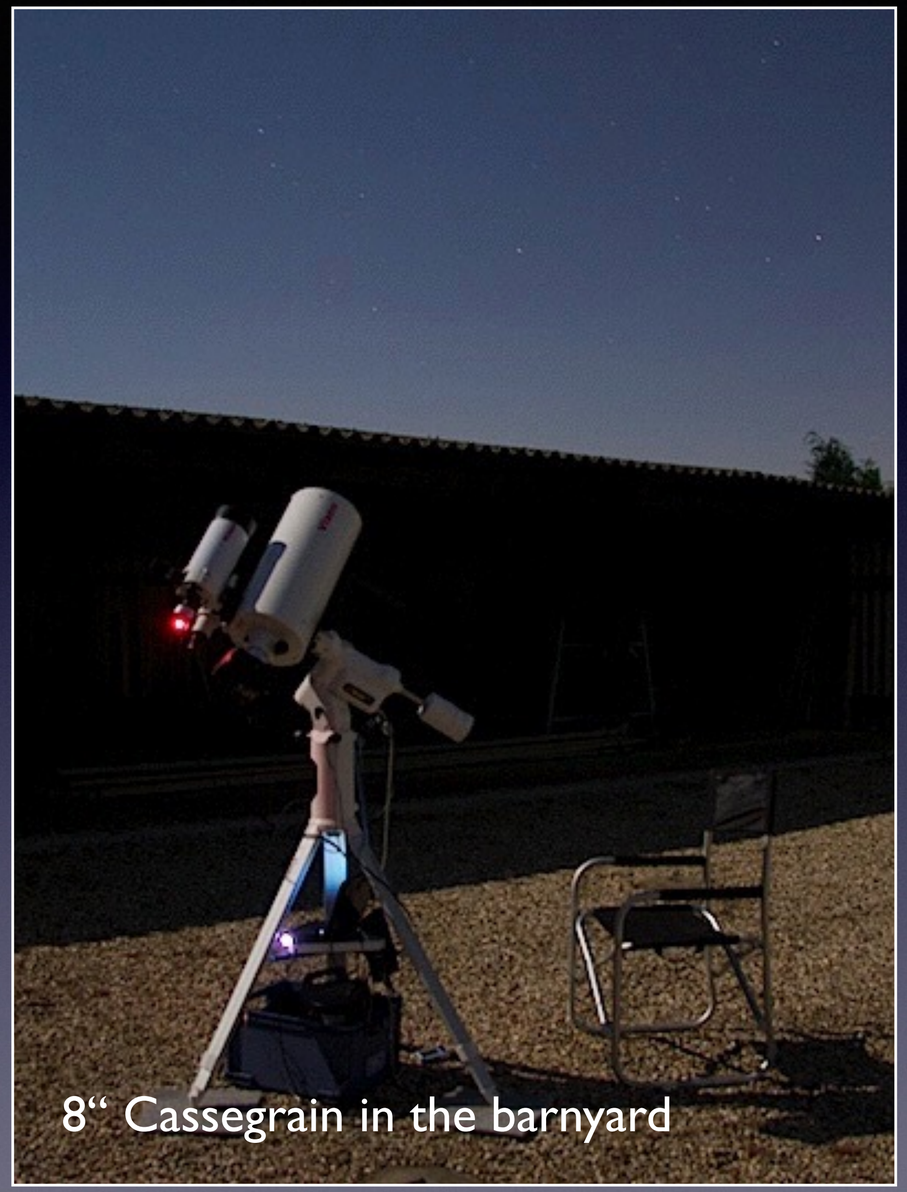
Spectrophotometry

Will it work the same with a small telescope?

1994
E. H. Geyer and **myself** believed that spectroscopy of objects below 10 mag is impossible to be done with small (amateur) telescopes.

2007
Paradigm: CCDs are obsolete.
Try photometry with CMOS (DSLR) imaging sensors.

2017
First results: Spectroscopy with CMOS sensors



8“ Cassegrain in the barnyard

About the project

CMOS Sensors

What can a small 8“ Cassegrain with a DSLR camera do for us?

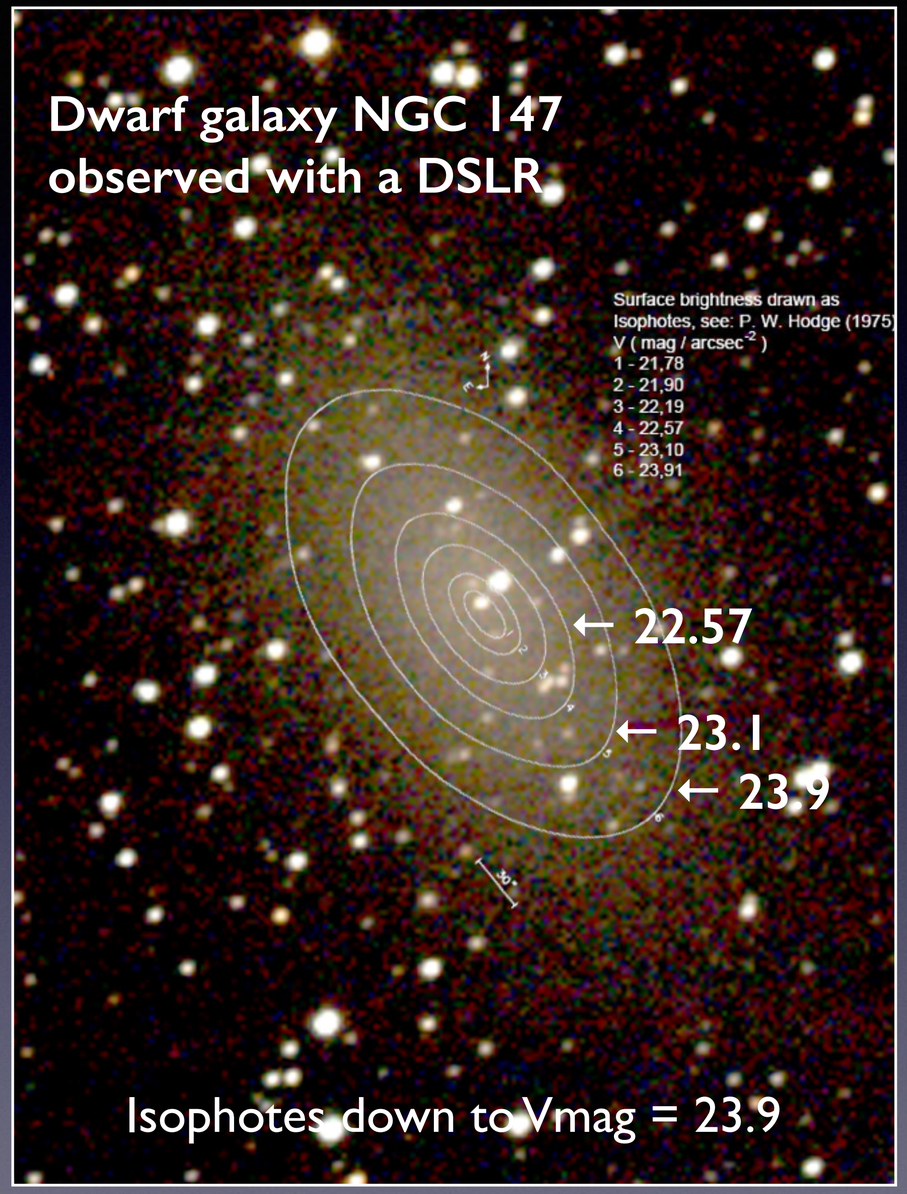
Challenge observations taking a 2.54 m telescope from year 1975.

Composite of 480 images of 30s exposure; total observing time: 4 h.

Hodge, P.W., 1976. The structure of NGC 147. Astron. J., Vol. 81, p. 25 - 29, 87

Bauer, T. *The RAW Image File Format Problem - Applications of Digital SLR Cameras in Astronomy and Science.* Proc. of the 4th Annual Meeting on Information Technology & Computer Science at the BA-University of Cooperative Education, H. Weghorn (Ed.), Stuttgart, ISSN 1614-2519, February 2008

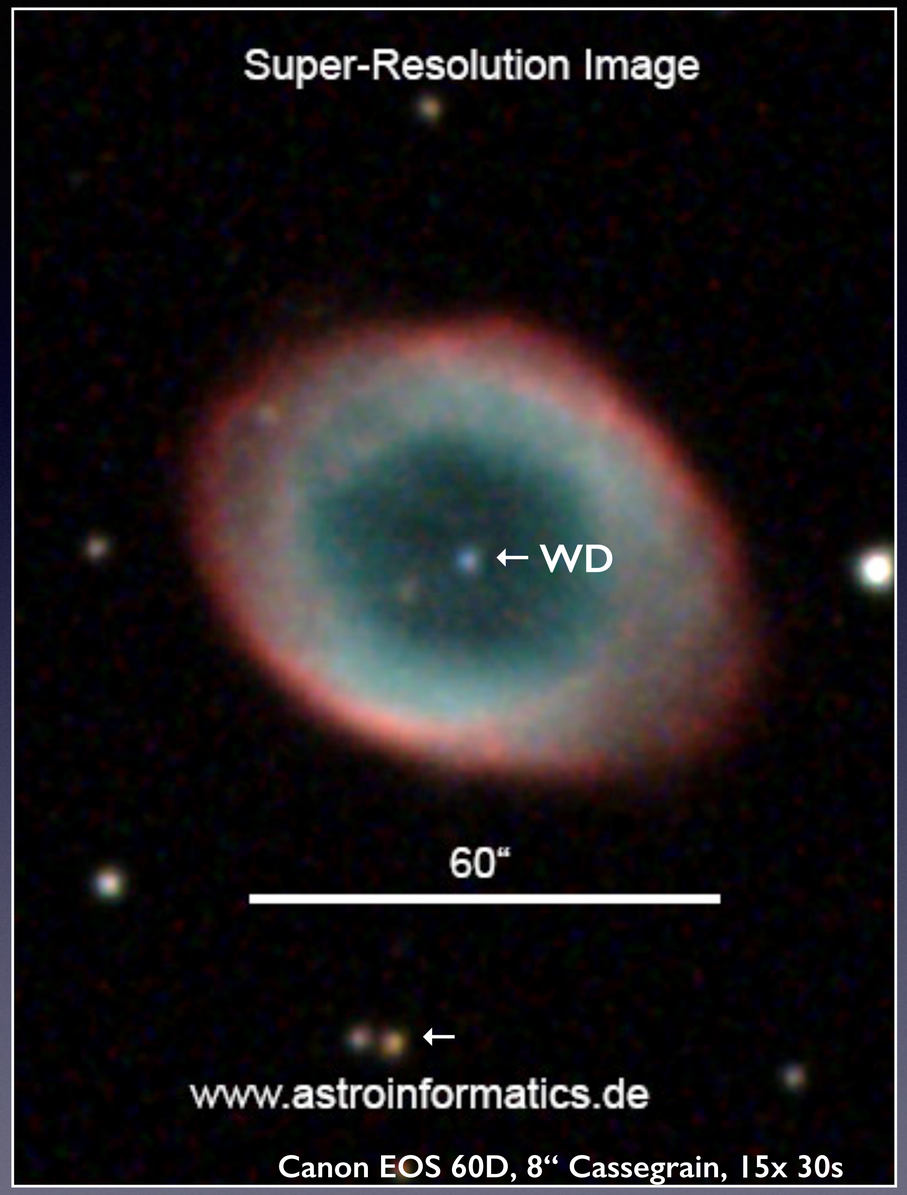
Bauer, T. *Astroinformatics - A Study about Constraints and Requirements for Next Generation Astronomical Image Processing.* Proc. of the IADIS Multiconference on Computer Science and Information Systems, Amsterdam.



Diffrraction-limited imaging

Super-resolution imaging with a Canon EOS 60D camera. The resolved visual binary star indicated by the arrow is represented by only three pixels and unresolved in the original images.

Note the different color distribution in red and green/ blue. This is also caused by different abundance of hydrogen, nitrogen and oxygen.

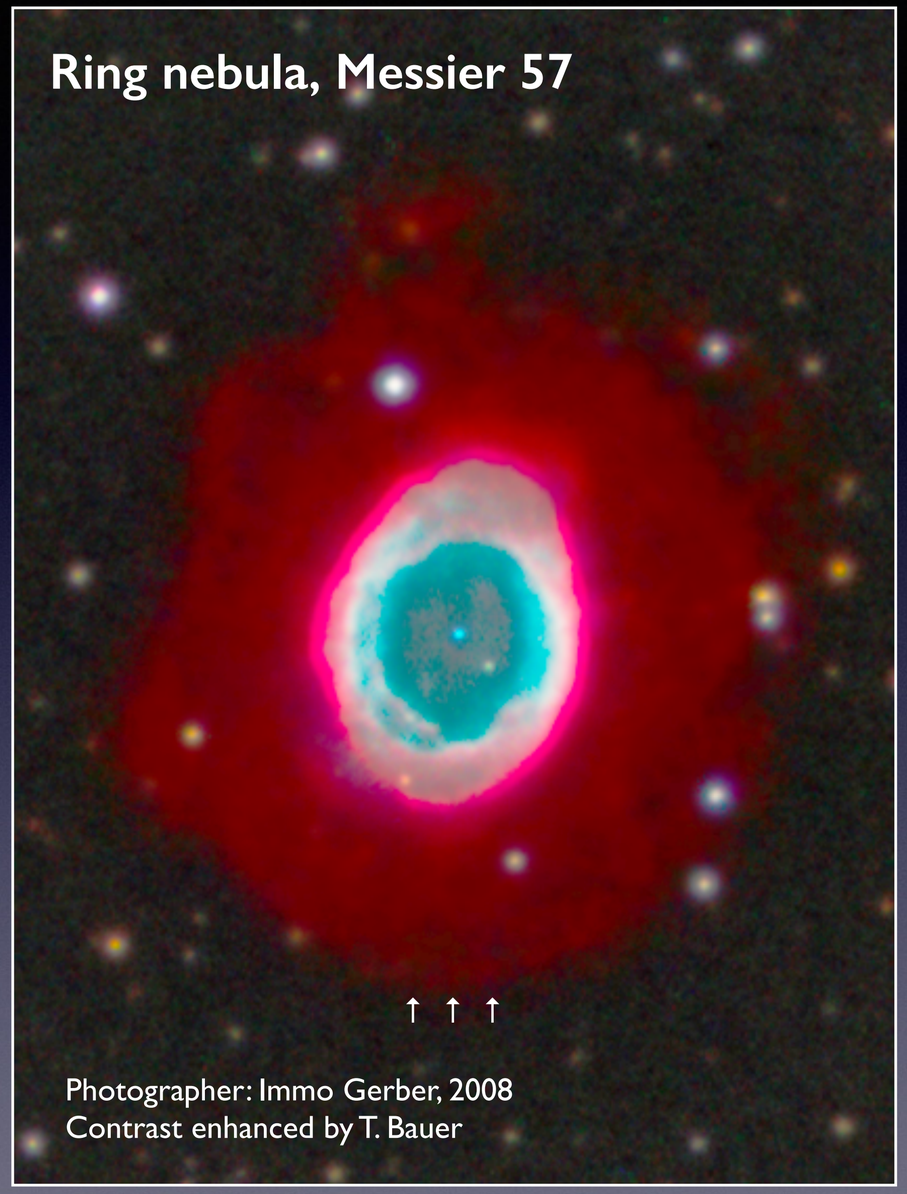


Bauer, T., 2011. *Super-Resolution Imaging: The Use Case of Optical Astronomy.* Proceedings of the IADIS International Conference Computer Graphics, Visualization, Computer Vision and Image Processing, p. 49-59, Rome, Italy

Outer shells of the planetaries

Certain planetary nebula like Messier 27 and Messier 57 are known to show one or more faint outer shells. These outer shells of the nebula are visible only to very long exposure imaging and spectroscopy.

Similar results were obtained from H_α observations earlier in the mid 90ies at the Hoher List Observatory. Unfortunately, certain original CCD images from the 1990ies are lost due to storage defects.



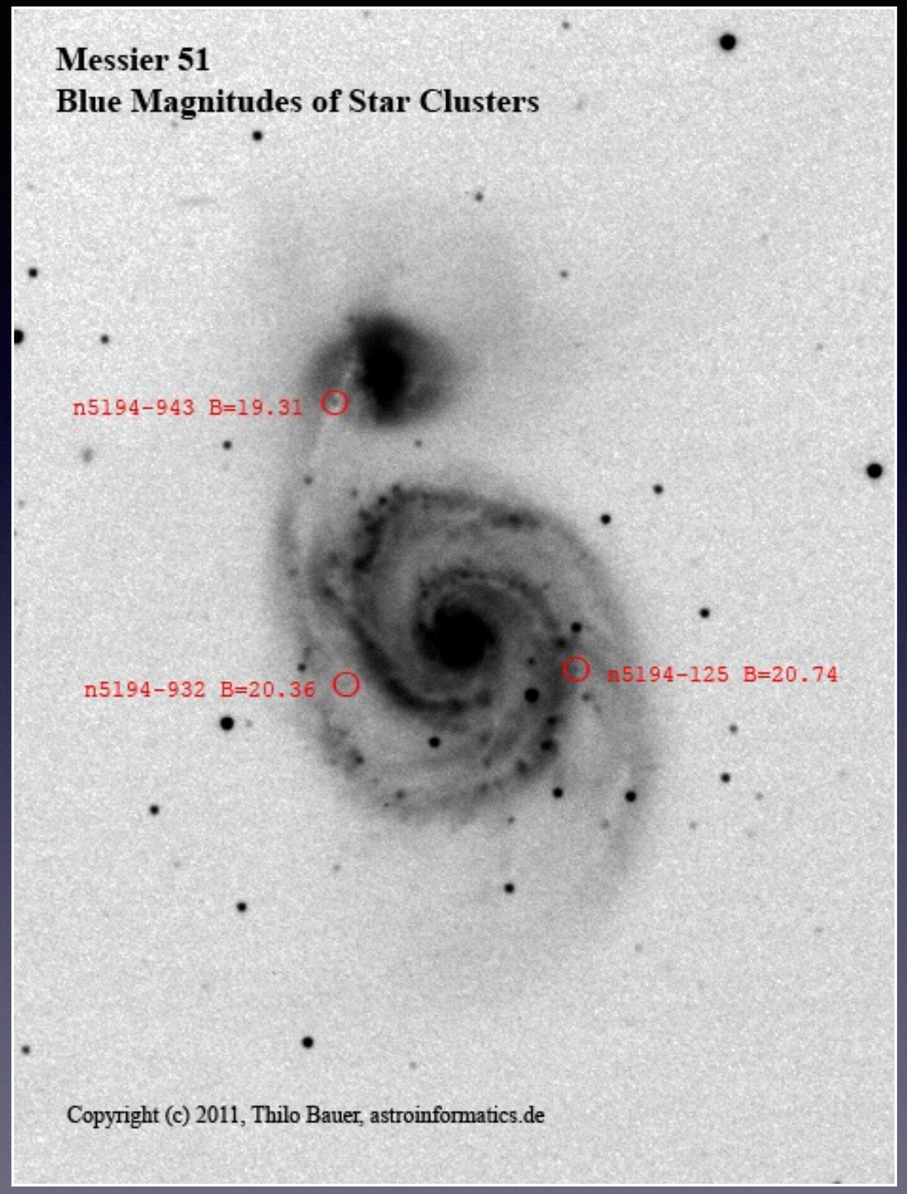
Extragalactic nebula

Because CMOS devices have a better blue response, one might typically try to observe OB associations and H-II regions in nearby galaxies.

This image is an experimental view on the famous spiral galaxy Messier 51.

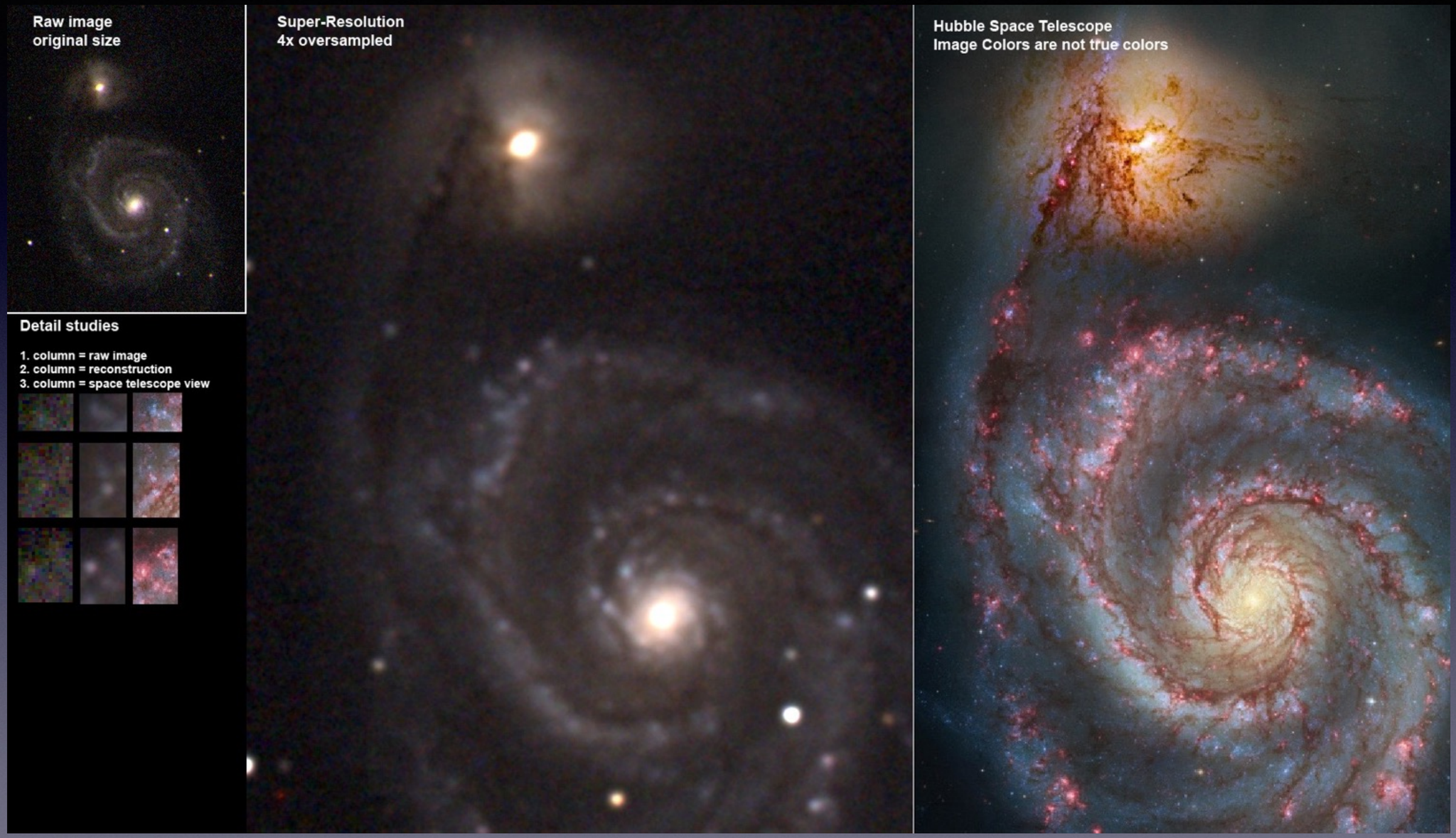
A simple DSLR camera is able to show H-II regions.

Limiting magnitude: V_{mag} = 20



About the project

M51

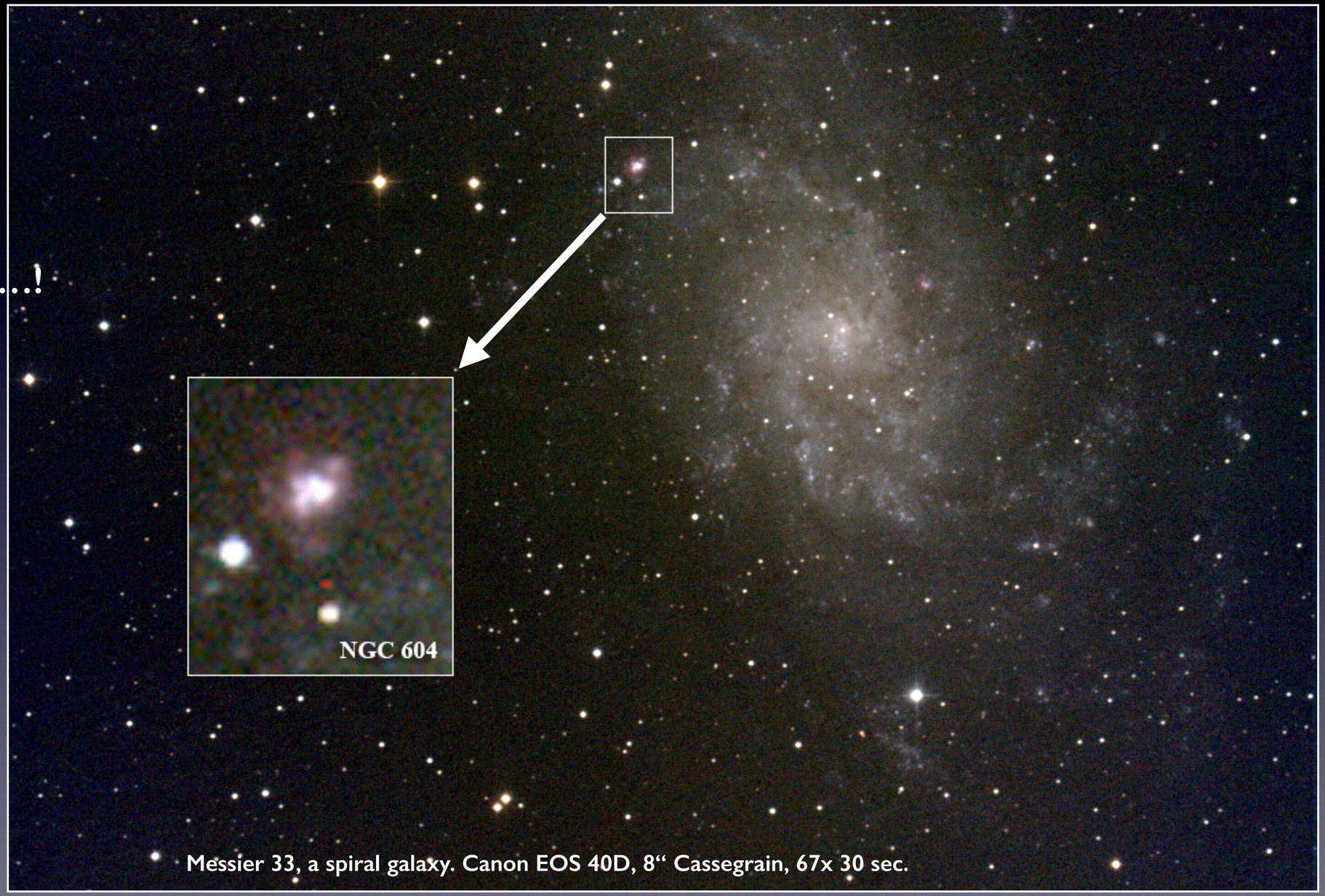


About the project

Extragalactic nebula

Could be challenging.

But hey, it's just a challenge…!

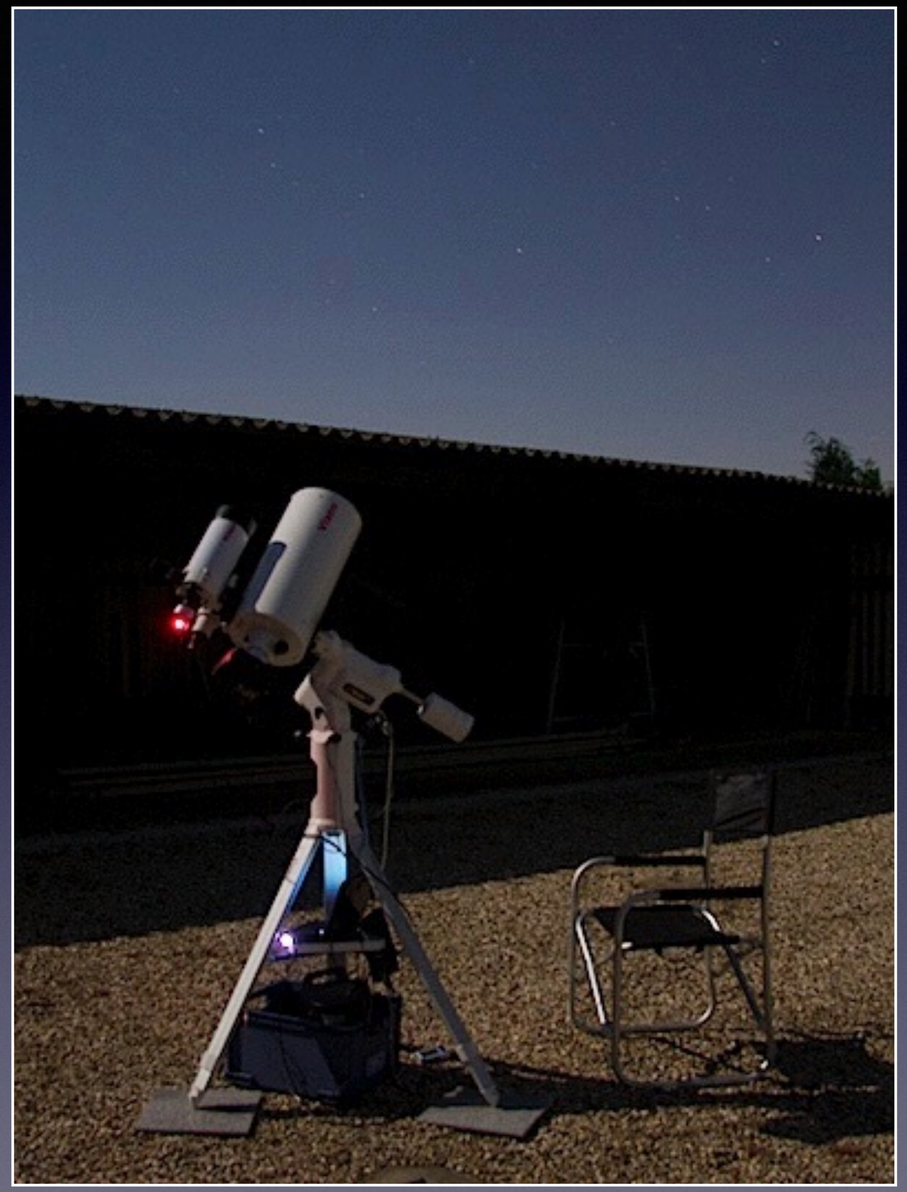


Messier 33, a spiral galaxy. Canon EOS 40D, 8“ Cassegrain, 67x 30 sec.

Spectroscopy + Imaging

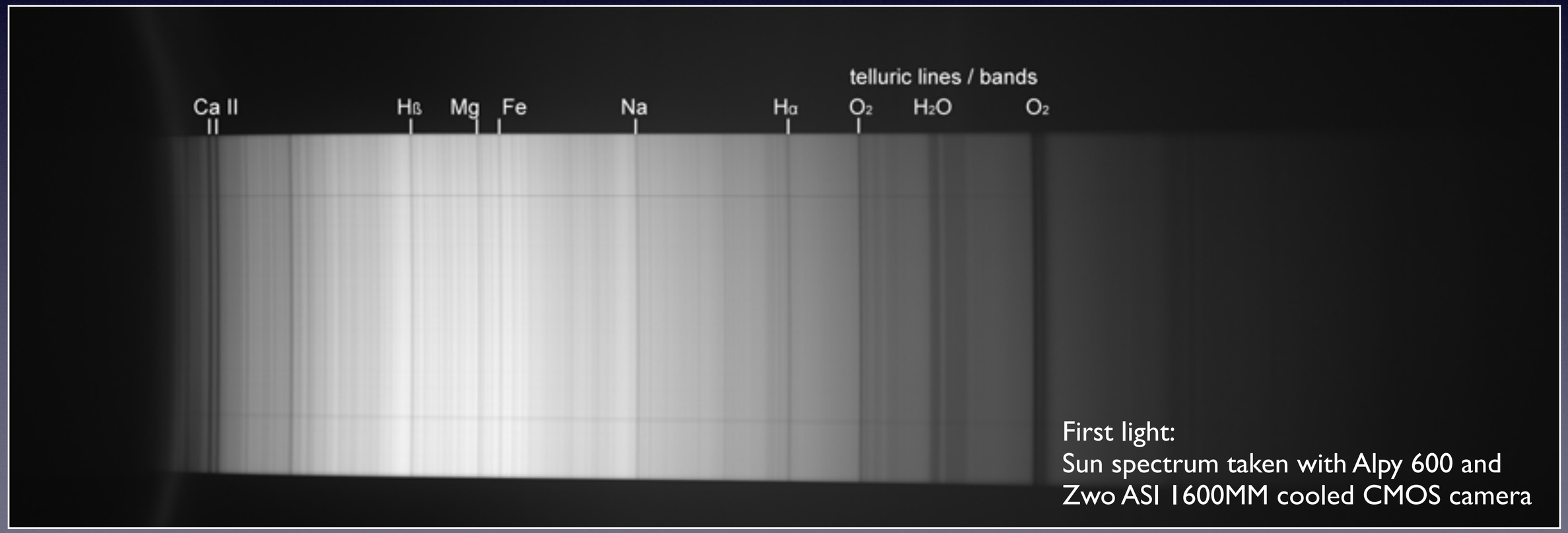
Special equipment is required for spectroscopy and imaging of gaseous nebula.

- Vixen VC200L, 8“ Cassegrain
- Alpy 600 spectrograph (low dispersion)
- Zwo ASI 1600MM cooled CMOS camera
- Narrow-band interference filters (imaging)
- $H\alpha$, $H\beta$, O-III, Si-II, N-II [6583]



First light with a CMOS device

The Alpy 600 spectrograph is designed for the visible wavelengths. Sensitivity of the ASI camera in the blue is way better than certain CCD devices.



First light:
Sun spectrum taken with Alpy 600 and Zwo ASI 1600MM cooled CMOS camera

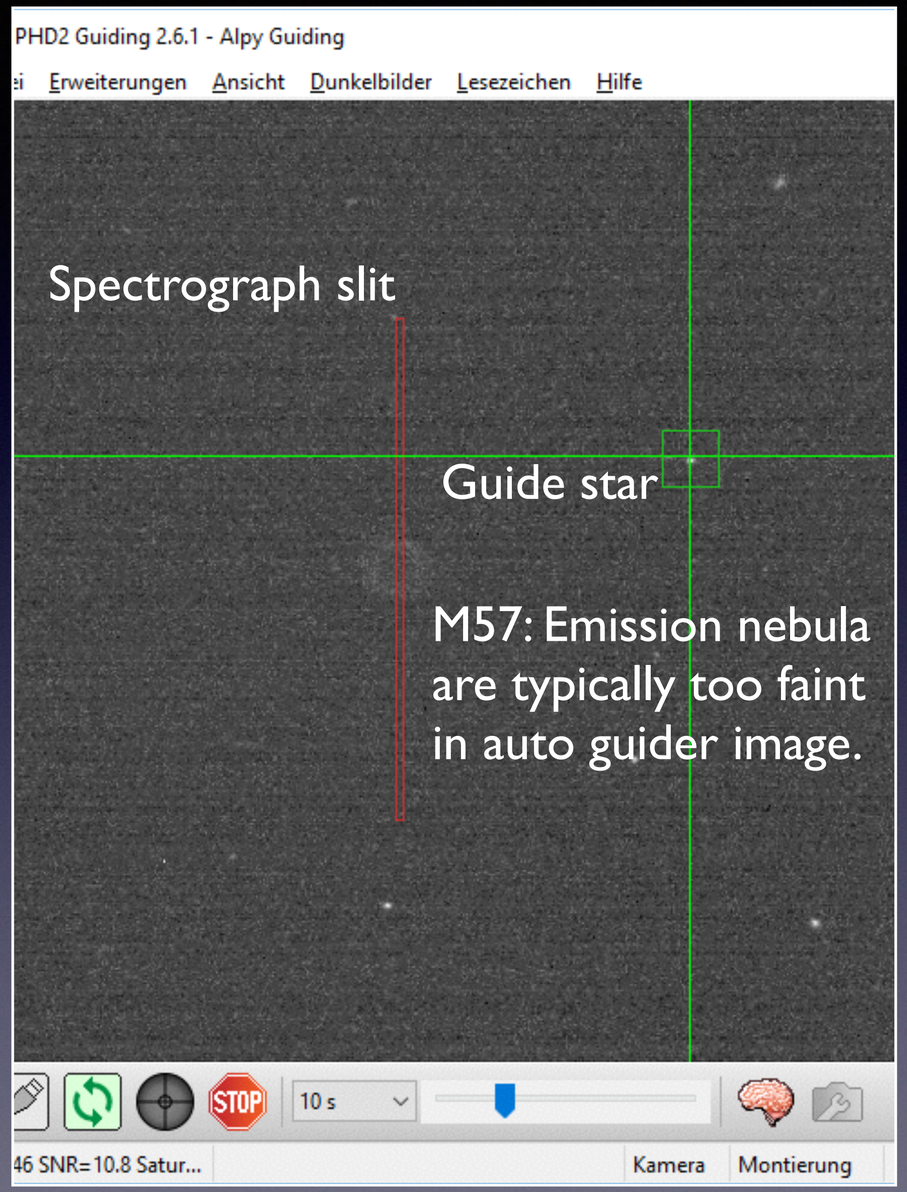
Spectroscopy

An auto-guider image snapshot is usually taken as a reference to document the slit position.

There is always room for improvement:

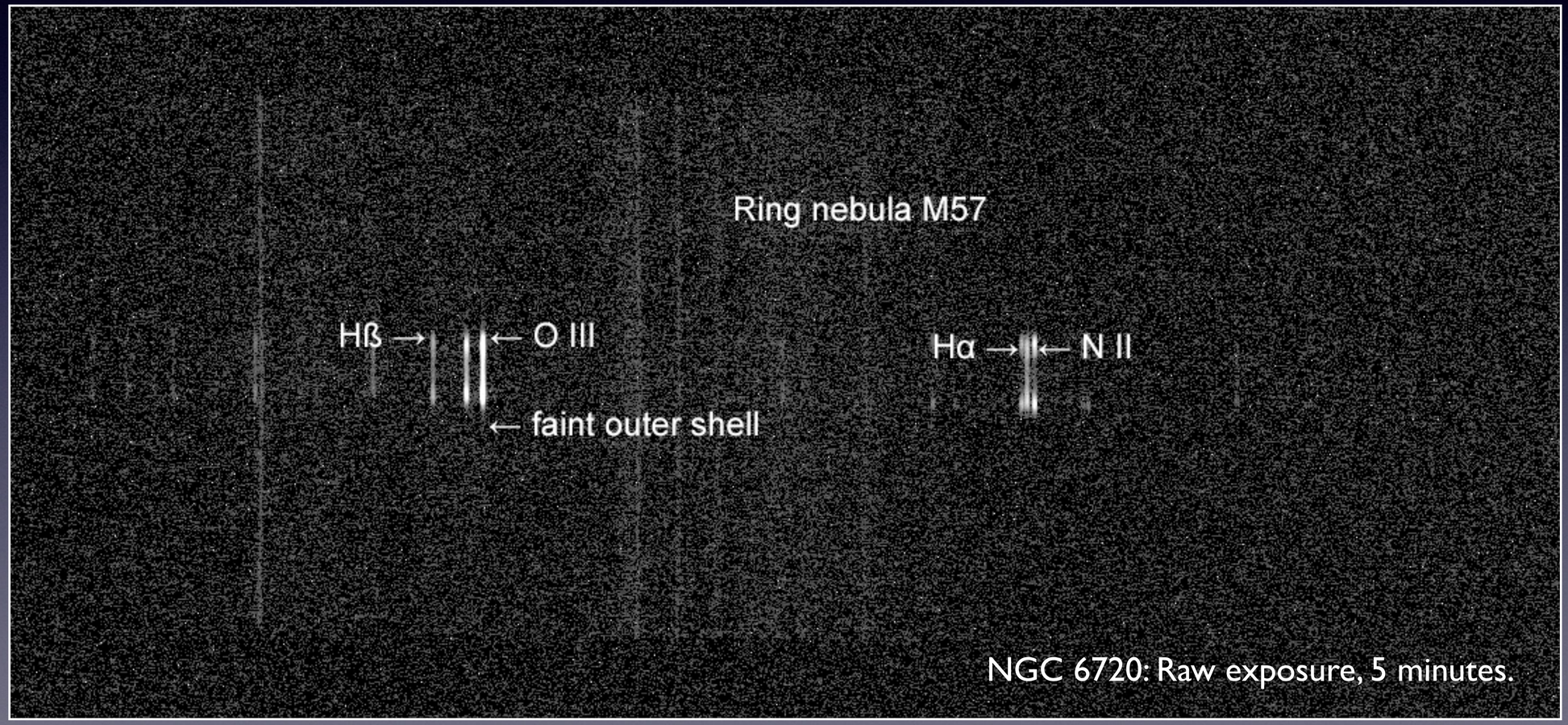
The Orion Starshoot auto guider has done its job well for imaging purpose.

However, this auto guider is not sensitive enough for the faint objects and will soon be replaced by a new generation CMOS device.



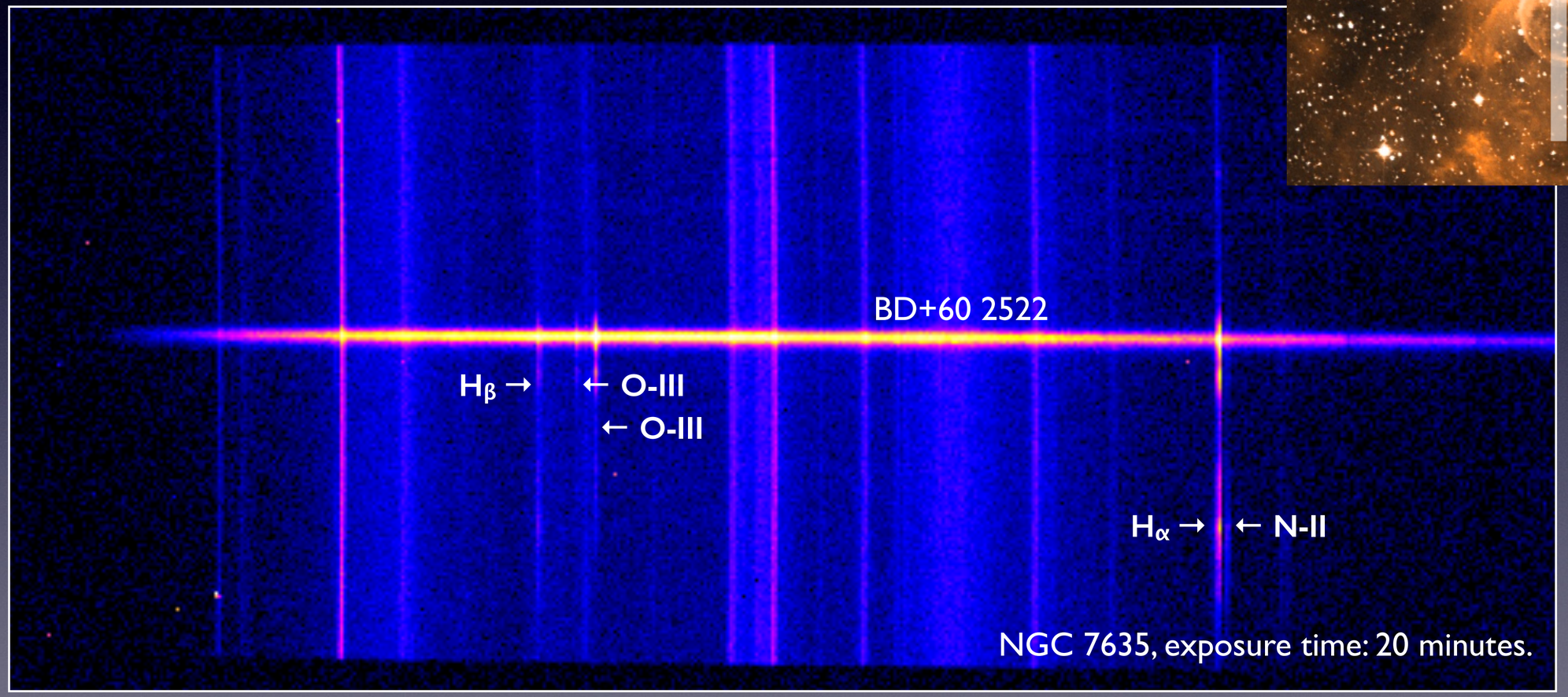
Instrumental tests

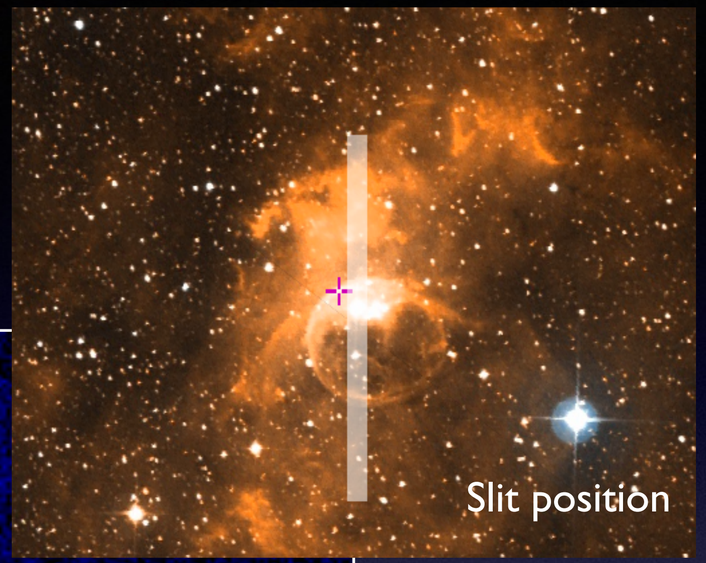
First tests taking spectra look very promising.



NGC 7635

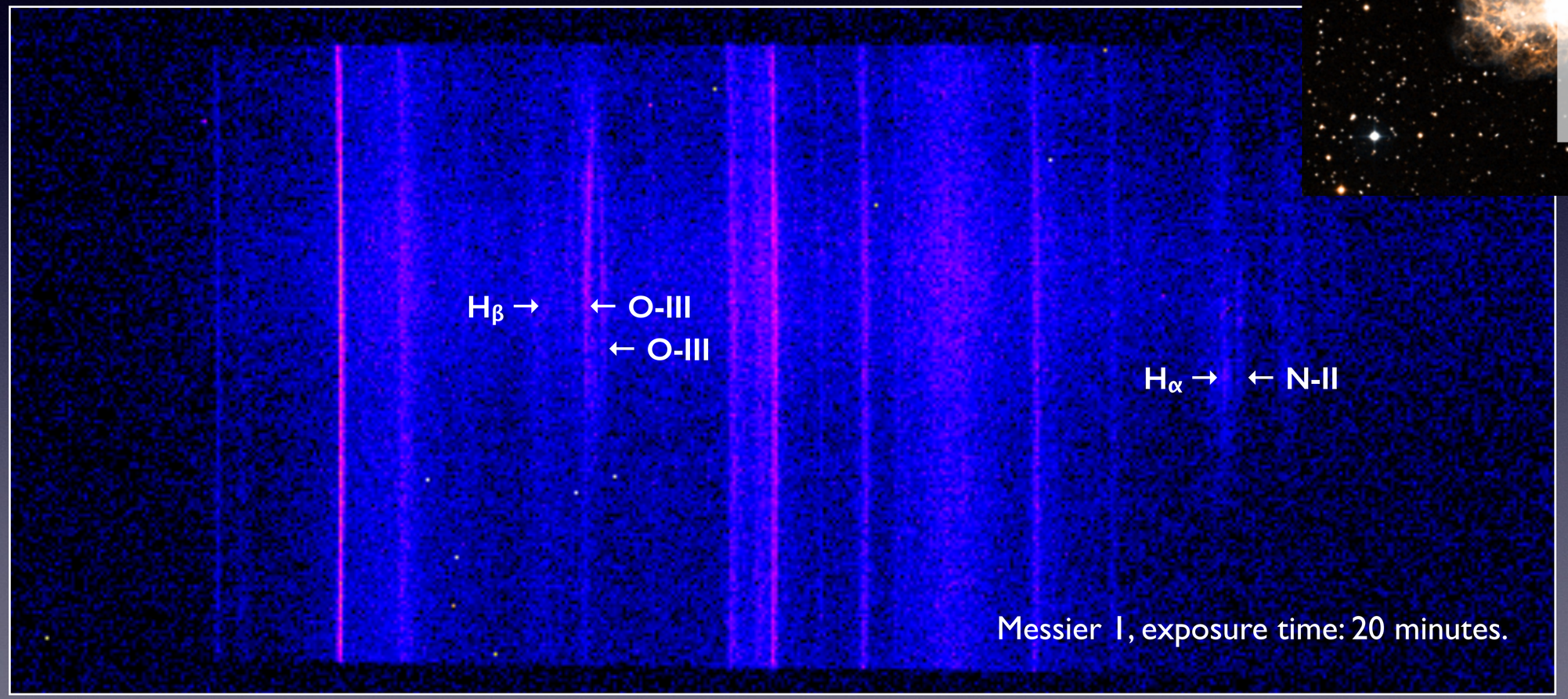
First light on Bubble nebula.

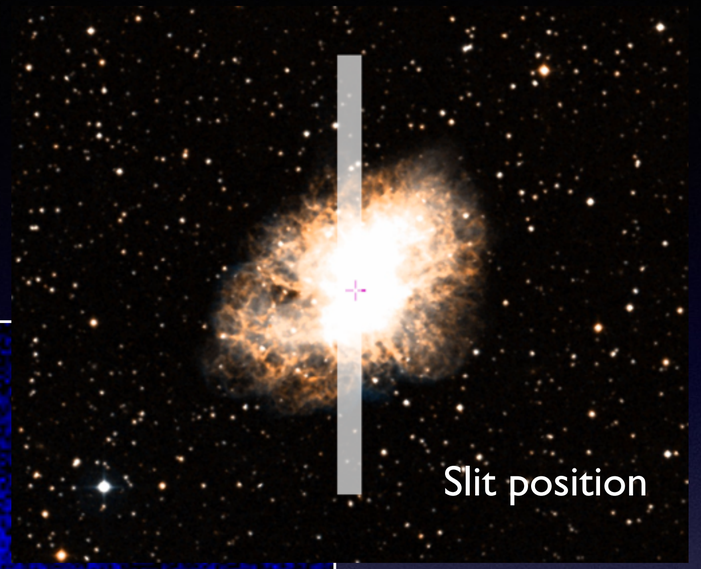




Messier 1

First light on a supernova remnant.

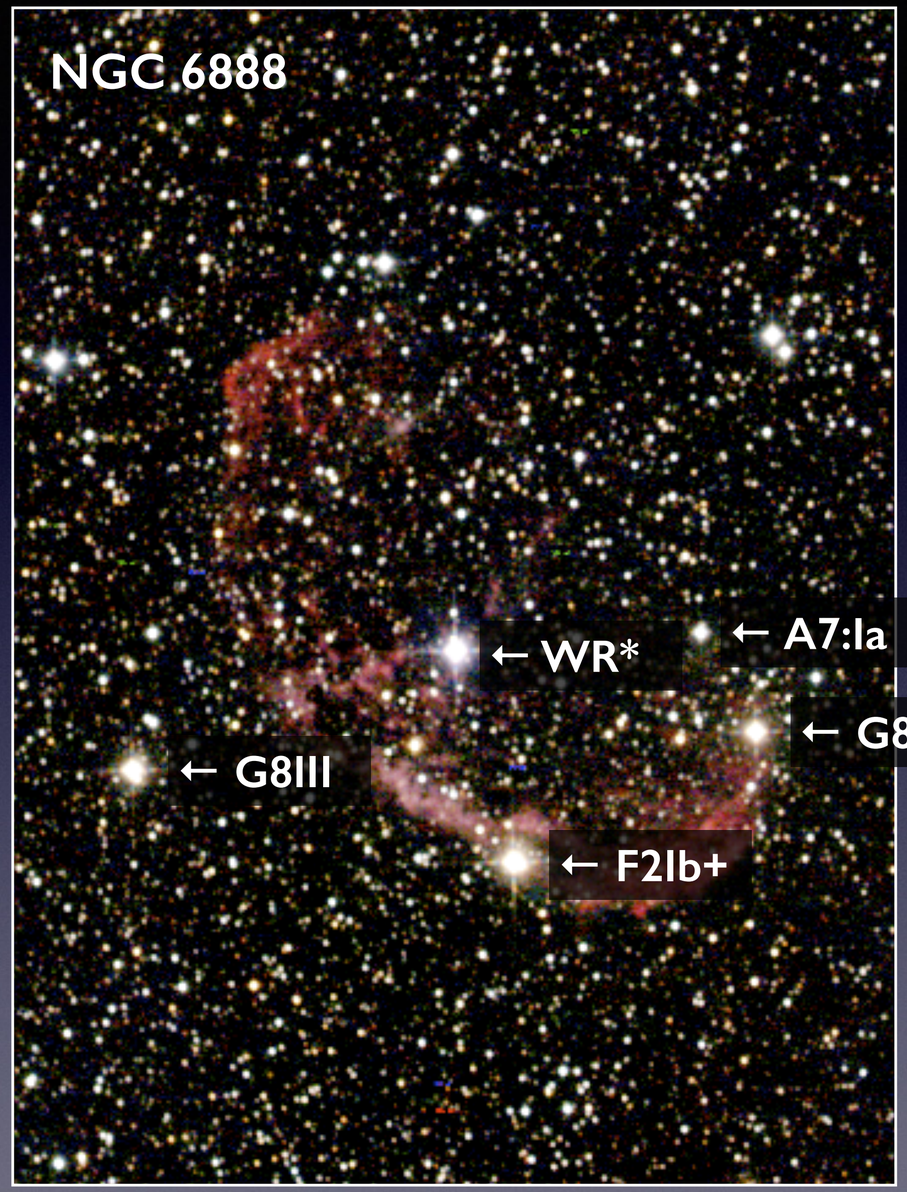




NGC 6888

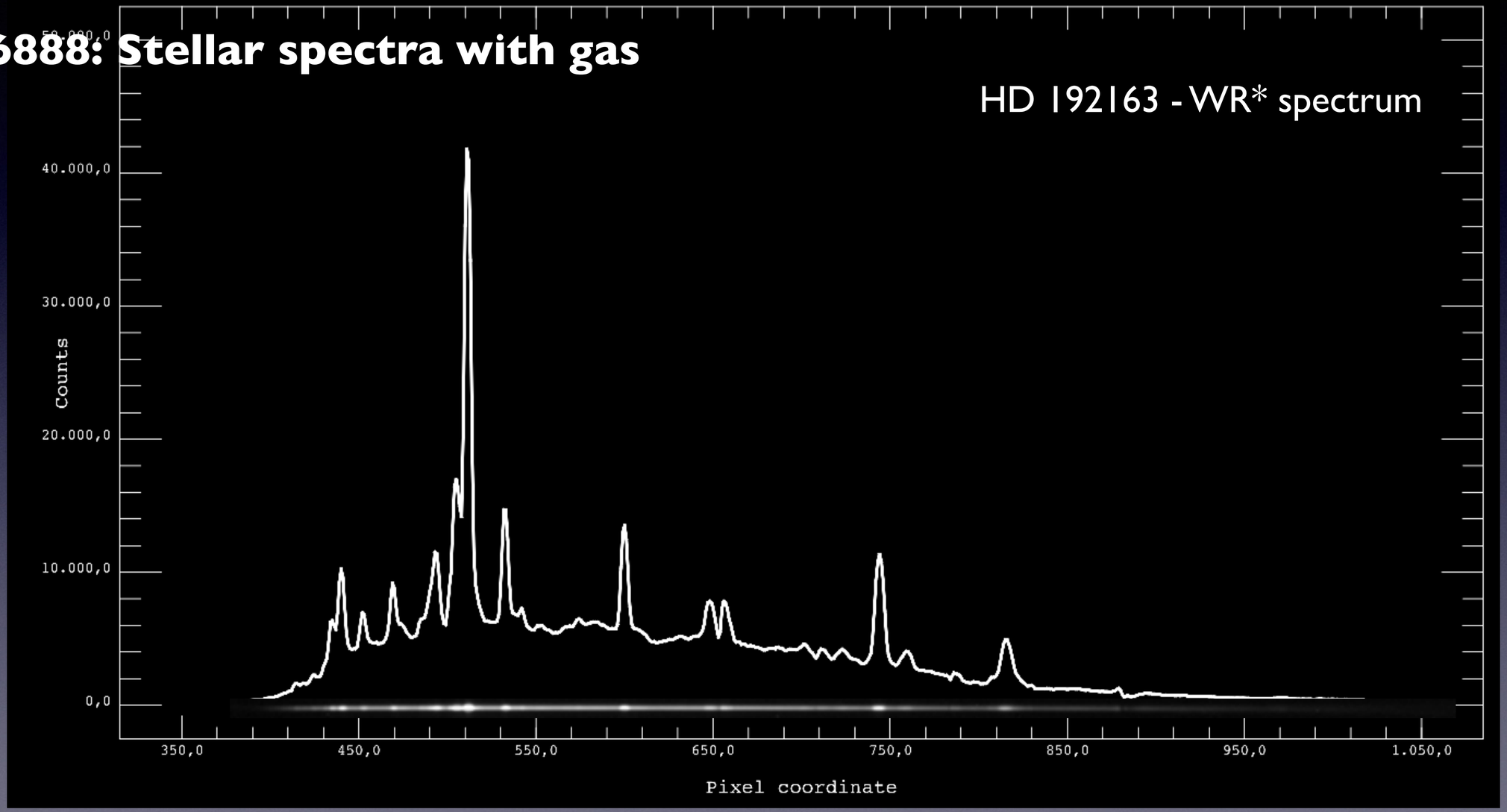
In the field of this nebula, the best candidate to excite the gas is the WR*.

Star	Type	Vmag
HD 192163	WN6(h)-s	7.5
HD 192182	G8III	7.2
BD+37 3827	F2Ib+	8.18
HD 192020	G8V	8.82
HD 228312	A7:Ia	10.1

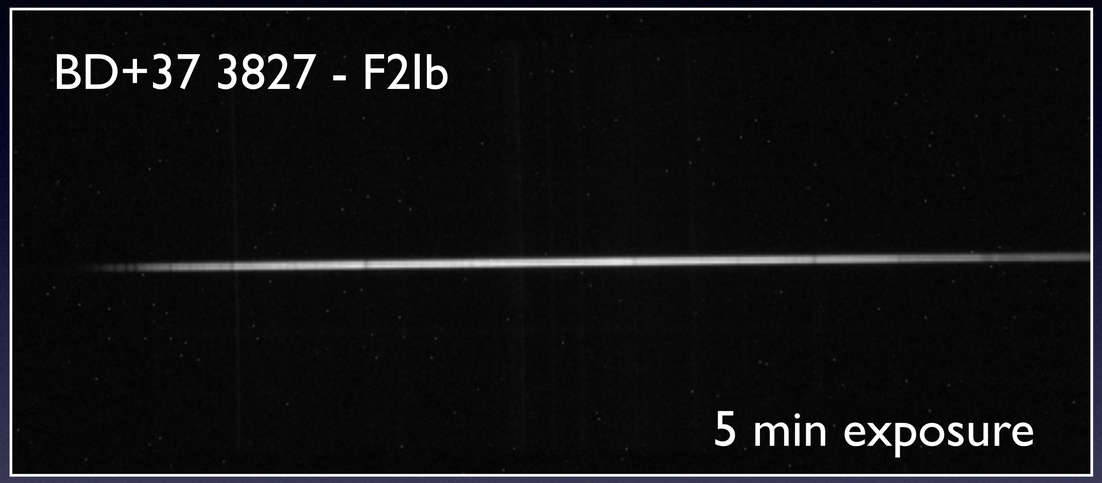


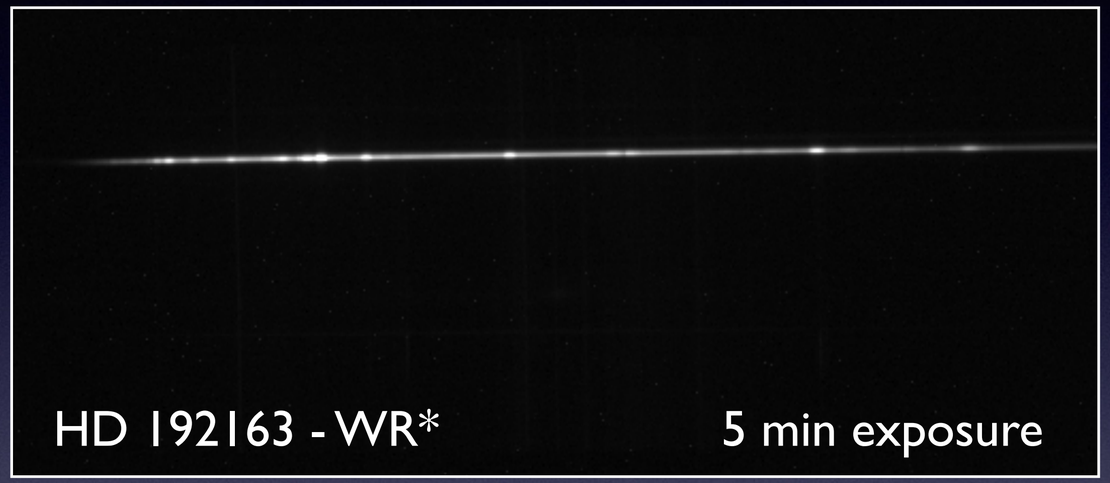
Canon EOS 60D, 8“ Cassegrain, 20x 60s

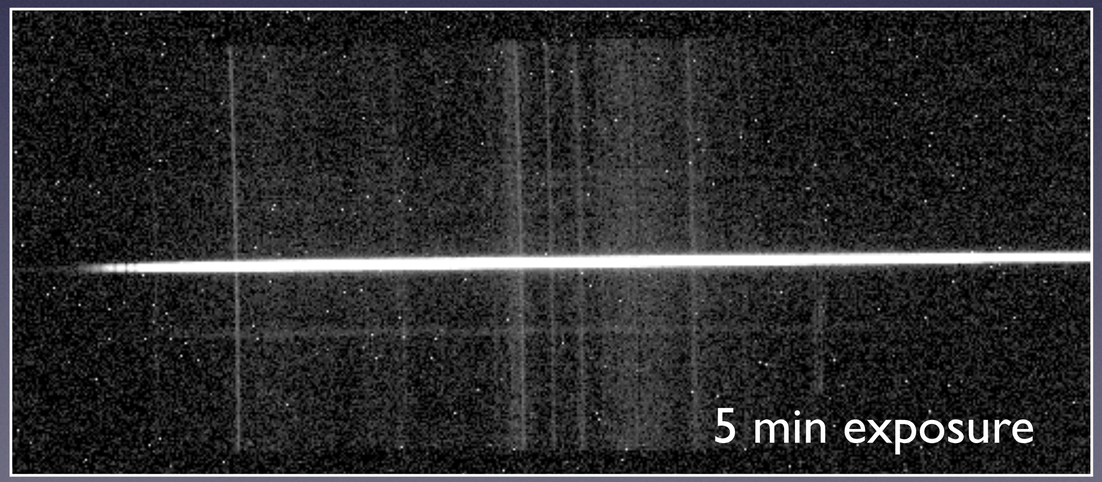
NGC 6888: Stellar spectra with gas

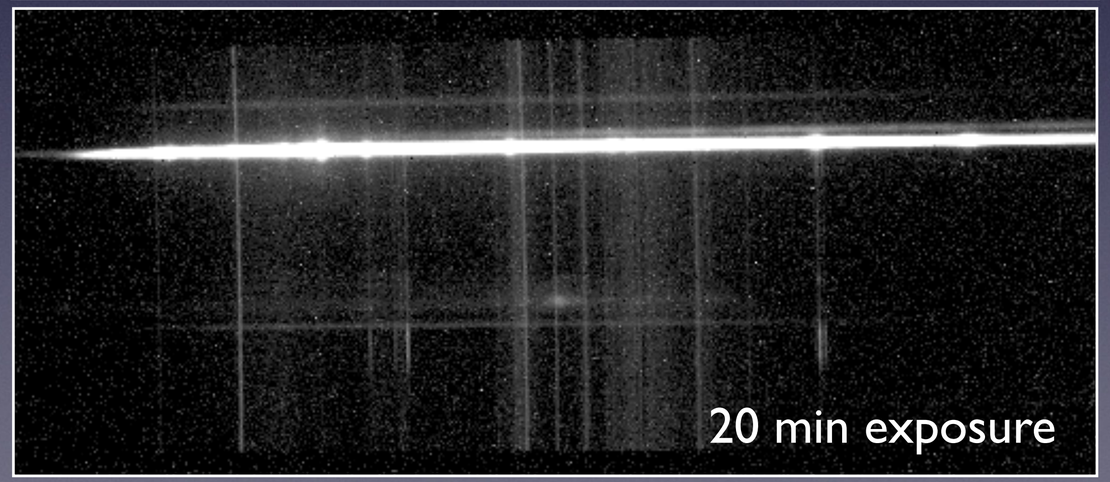


NGC 6888: Stellar long-slit spectra



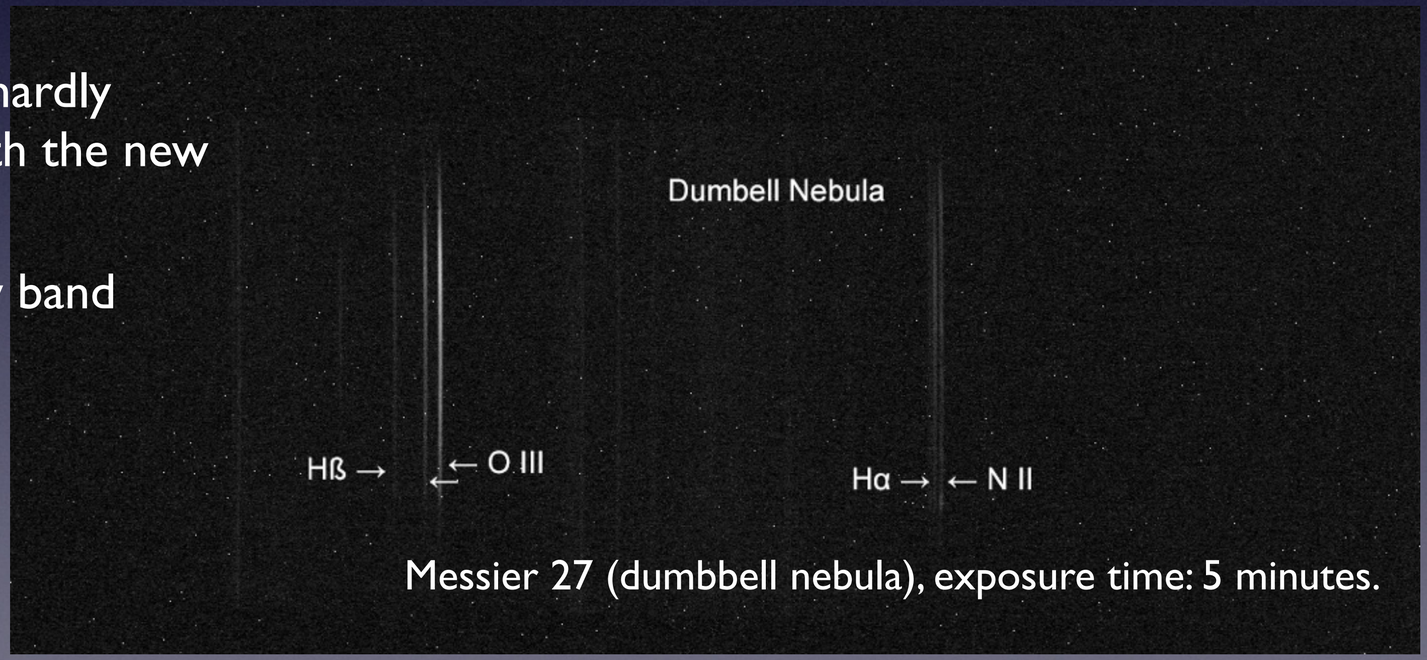






Status

- First spectroscopic observations with the new ZWO CMOS camera look very promising
- Very low CMOS camera read-out noise: ~ 1 e^-
- Excellent device for spectroscopy of the faint nebulae with a small telescope
- From every object, that the DSLR could hardly demonstrate, spectra can be achieved with the new CMOS camera
- Spectrophotometric imaging with narrow band filters started in parallel and in progress



Messier 27 (dumbbell nebula), exposure time: 5 minutes.

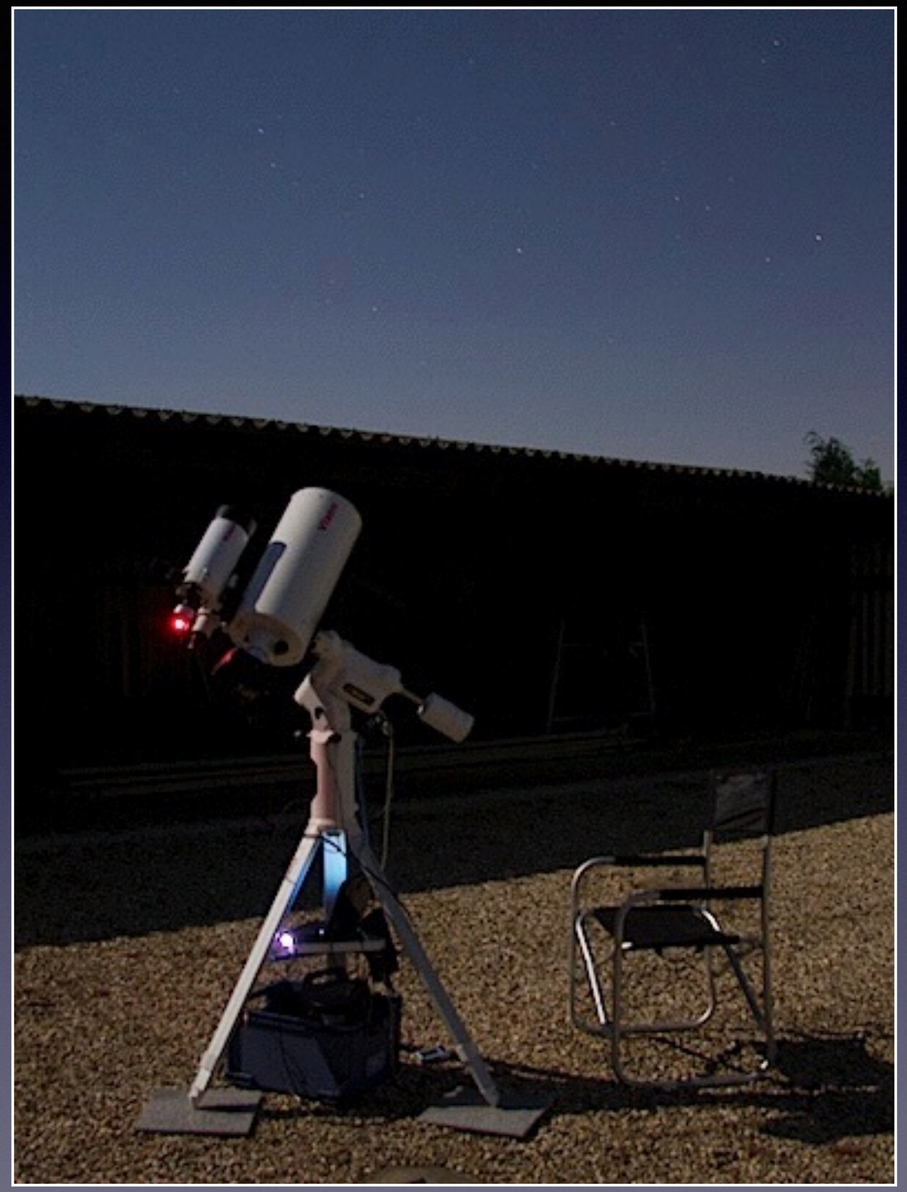
Conclusion

It took us 22 years of achievement, but…

Hey, we shrinked the 1m Cassegrain to a 8“ telescope in the barnyard…!

How did we manage that?

Any suggestions?

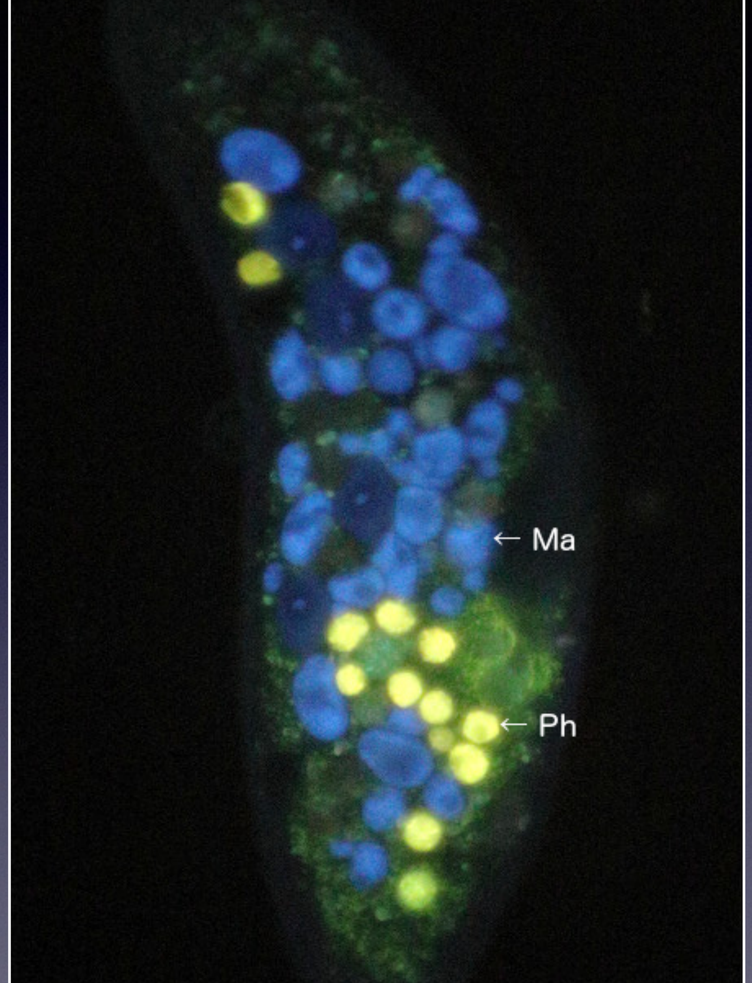


Thank you for your attention!

Questions…?

Do not hesitate to contact me: http://www.astroinformatics.de

Bad weather astronomy:
Rules are the same…



Paramecium caudatum,
fluorescence staining