Astrophotography with next generation EMCCD cameras

Carsten Dosche (October 2009)

Application Note

Introduction

Astrophotography has a long tradition reaching back nearly to the beginning of photography itself. However, it has been restricted to professional users und few amateurs as it required expensive equipment and special handling of the chemical films. Since the early 90's, the development of CCD and CMOS sensors has revolutionized amateur astrophotography. These new sensors offered not only superior sensitivity, but also, combined with the parallel development of computer techniques, the benefits of electronic picture processing and automated star tracking for the still long exposure times. With the EMCCD camera concept a new generation of sensors has been developed providing sensitivity down to the single photon regime. EMCCDs nowadays are widely used for single molecule spectroscopy and professional astronomy, but can also be beneficial for amateur astrophotography.

General CCD Astrophotography

Digital astrophotography is always limited by the S/N ratio which can be achieved with the detection system. The sensitivity of a CCD detector is mainly limited by quantum yield and dark current of the chip.

Generally, the photon quantization and the limited quantum yield (not every photon will generate a charge on the chip) cause photon noise. For normal applications this will never be a problem as the number of detected photons is always much higher than the photon noise floor. However in low light applications such as astrophotography this will become relevant if only few photons are detected. Moreover, there is an additional noise source caused by the chip electronics, namely dark current of the chip and the noise related to it. To overcome this noise problem in astrophotography long exposure times are required in order to generate as much signal as possible above the noise floor. In principle, this can achieved either by increasing the exposure time for a single frame or by acquiring multiple exposures. The effect of increasing the total exposure time by stacking many exposures is shown in Fig. 1. A single frame is quite noisy. After sampling 5 or 50 frames, respectively, the enhancement of the S/N ratio is obvious.

In order to obtain an optimal S/N ratio before read out, the single frame exposure time usually is increased until the full dynamic range of the CCD chip is used. These long exposure times, however, give rise to the need for sophisticated guiding procedures to ensure an adequate long term tracking of the object in focus. Therefore it would be desirable to acquire many short exposures instead of one long exposure. However, for conventional CCD cameras this is not possible. Because the direct signal from the CCD chip is not high enough to be processed by the A/D converter, it has to be pre amplified. The pre amplifier, like all electronic devices, causes noise which is usually called the read out noise. The signal from the CCD chip must exceed this read out noise, elsewhere any signal which does not exceed the read out noise will be disrupted in the pre amplifying process. Normally, the only solution is to increase the exposure time until enough signal is gathered on the CCD chip.

A technical solution for this dilemma has been invented with the EMCCD cameras. Here the signal is amplified by an EM gain register directly on the chip before read out. This provides the possibility to make shorter exposures without loosing information to the read out noise. The effect of the EM gain is demonstrated in Fig. 2. In the gain off condition, even after stacking 30 exposures the noise reduction is not sufficient for the picture processing of weak nebular structures or faint stars. With the EM gain set to 200, this is no problem and even some parts of the very weak nebular halo become visible.

Astrophotography using the Luca EMCCD Platform

EMCCD cameras are still exclusively available for scientific applications. Apart from the cost factor, the commonly used EMCCD camera systems are not suitable for amateur astronomy due to weight, power consumption and computing power requirements for a high end PC system including a PCI card is needed. With the Luca EMCCD platform from Andor Technology an EMCCD system has been developed which meets the requirements of amateur astrophotography like USB connection of the camera, low weight and a prize in the area of other high end CCD cameras commonly used for astrophotography.

The Luca EMCCDs are available in two versions, the Luca-S with a 658 x 496 Pixel chip and 10 µm pixel size and the Luca-R incorporating a 1004 x 1002 pixel chip and 8 µm pixel size. The camera system is equipped with a 14 bit A/D converter. This digitization depth is sufficient as the full pixel capacity is 26,000 electrons. The weight of about 600 g is in the range of large commonly used eyepieces and therefore acceptable for standard mountings. The CCD chip is thermoelectrically cooled to -20°C in order to reduce dark current and electron noise. For EMCCD sensors this is essential as the thermal noise will also be magnified by the EM register. Nevertheless, the power consumption is below 20 W and the camera could be driven by car battery if necessary. Although a powerful computer system is recommended for obtaining the full performance of the system, a small netbook equipped with an Intel Atom processor as available since 2008 is completely sufficient to drive the camera on the field. The camera comes with a C-mount connection and can be easily attached to any telescope using the standard C-mount adapters to M42, T2 or 1.25" connectors. The camera has a relatively short backfocus and therefore can be used with most telescopes without modification of the focal path.

When using a Luca EMCCD camera for astrophotography, some points have to be taken into account. The Luca EMCCD cameras have been invented for microscopy applications. Thus, long term exposures in the range up to 60 sec have not been in focus of development. Although the EMCCD chip is free of hot pixels for exposure times below 1 sec or EM gain-off conditions, by using long time exposure every "warm" pixel will be magnified by the EM gain register and appears as hot pixel in the image. The same is true for every weak chip inhomogeneity which will also be amplified. Therefore for every gain-exposure time combination a dark frame has to be collected. Luckily the chip cooling works very accurate and thus this procedure has to be performed only once. In order to obtain noise free dark frames an average stack of about 100 frames should be taken and saved as 16 bit Tiff file. When needed it can be loaded as background image for acquisition by using the "arithmetic operations" function of the camera control software Solis. The second point is about exposure time. Although the camera appears very sensitive, it does not generate photons, it just prevents weak signals from being wiped out by the read out process. Thus the single exposure time can be reduced without loosing information. However, the photon noise is amplified as well as the signal itself. Therefore the total exposure time has to be the same as for conventional CCDs with comparable quantum yield to obtain an adequate S/N ratio. Only the exposure time for the sub frames can be significantly lower. Finally, for astrophotography the Luca-S has relatively large pixels and a small field of view. The latter problem can be easily managed by making mosaics. For the pixel size, normally the focal length of the telescope has to be matched to the pixel size. For 10 µm pixels this would inquire that a focal length larger than 1 m should be used. For smaller focal lengths the pictures will be undersampled what means that stars are not longer projected as a Gaussian profile. Here the Drizzle algorithm which was originally developed to enhance the quality of Hubble Telescope pictures can be used. Details can be found on the webpage **www.stsci.edu/hst/wfpc2/analysis/drizzle.html.** With this method the resolution of the pictures can be enhanced by a factor of 2 without loosing S/N ratio.For this method a relatively large number of single frames is required, for each frame the object displaced on a sub pixel scale. Here the exposure technique applied to the EMCCDs, namely making many short exposed frames is ideal for using the Drizzle technique. The effect of the Drizzle algorithm can be seen in Fig. 3, the upper picture stacked conventionally, scaled by a factor of 2 and linearly interpolated, the lower stacked by using the Drizzle function.

Field Tests

For testing the suitability of the Luca EMCCD platform for astrophotography a Luca-S was used in combination with telescopes of different focal lengths between 0.43 m and 6 m. Most exposures were performed on a not modified commercial EQ6 mounting under mid European near city conditions. For the generation of colour pictures dichroic filter sets were used, broadband filters with ~75 nm bandpass for red, green and blue (center wavelengths 460 nm, 530 nm and 650 nm) and narrow band filters with 8 nm bandpass for the SII, Hα, OIII and Hβ bands. Raw exposure series were taken in the kinetic mode, exported as 16 bit Tiff files and processed with the software Fitswork and Deepsky Stacker. For most applications, stacking of 25-50 frames was necessary to obtain a S/N ratio of >500, which is absolutely sufficient for generating high quality pictures. The EM gain was set to 200.

Galaxies and Globular Clusters

Galaxies and Globular Clusters have in common that they emit a continuous spectrum what renders the use of narrow band filtering useless. Apart from "near" galaxies like the Andromeda Galaxy M31 these objects are relatively small and require a focal length of about 1 m. For globular clusters exposure times between 5 and 10 sec appeared to be useful. Longer exposure times resulted in burn out of the centres. For galaxies exposure times of 20 sec were needed to ensure a sufficient use of the dynamic range of the camera.

A special issue is represented by dark and reflection nebulas like the Iris Nebula NGC 7023. These objects require a very dark sky background and cannot be taken successfully from city sites. However, under dark sky conditions the dynamic of the Luca-S is sufficient for these faint objects.

Galactic Nebulas

Our galaxy bears a large number of diffuse gas clouds like the Omega or the Eagle Nebula, which consist mainly of hydrogen, sometimes also oxygen and sulphur. Here the use of narrow band filters greatly enhances the contrast. Especially the high sensitivity of the Luca S in the red spectral region is beneficial for the detection of the hydrogen Hα band (656 nm) and the usually weak SII band (675 nm). As these nebulas require mostly large fields of view and short focal lengths, the Drizzle method can readily applied and gives excellent results. The same is true for super nova remnants like the Veil Nebula NGC 6992. Exposure times varied from 5 sec to up to 30 sec.

Planetary Nebulas

Apart from some nearby representatives such as the Dumbbell Nebula M27, planetary nebulas display a high brightness but are very small. Therefore very long focal lengths exceeding 3 m are required. This causes severe problems as accurate guiding becomes increasingly difficult with growing focal length. In addition, air disturbances from the atmosphere, the "seeing", also has increasing impact on the picture quality. The best way to conquer these two problems is to reduce the exposure time as far as possible. Here the advantages of the EMCCDs turn the Luca-S into the ideal detection system for planetary nebulas. Even for focal lengths of up to 6 m, good results can be achieved at exposure times around 2 sec. However, this short exposure time allows taking 100-500 single exposures. This already marks the domain where lucky imaging starts being useful for improving the picture quality. Usually only 10 % out of one exposures series taken at 6 m focal length could be used for further processing.

Planets

Due to the high frame rate of 30 fps, the Luca-S is also suitable for lucky imaging of planets and the moon. For the very bright planet Jupiter it can even operated with gain off. Usually a set of 500 frames is sufficient to obtain a stacked image where the S/N ratio is good enough for image processing.

Summary

The Luca-S can be used as a universal workhorse system for various applications in amateur astronomy. Hereby the possible use of the camera is not just limited to imaging. It can also be used for spectroscopy or variable star photometry, applications gaining increasing importance even in amateur astronomy.

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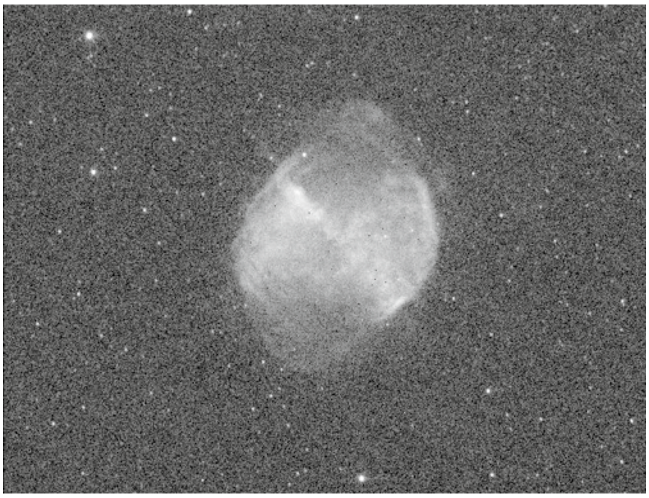
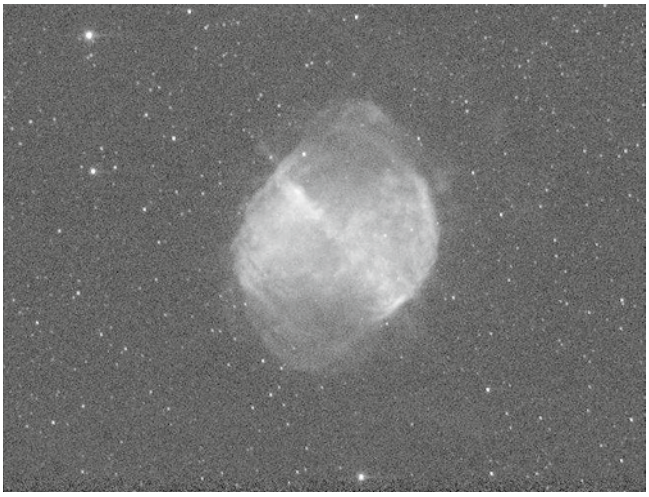


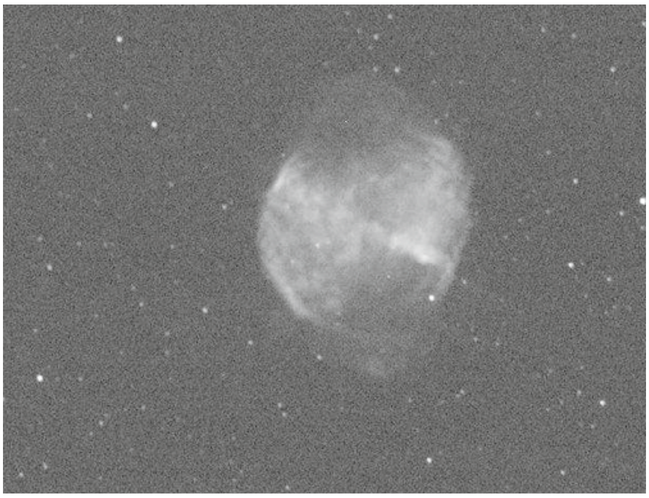
1a



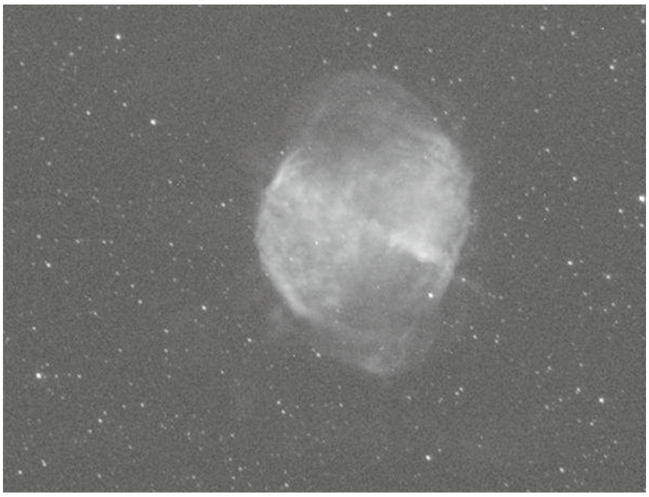
1b

1c

Fig. 1: Effect of stacking 1 (1a), 5 (1b) and 50 (1c) 20 sec exposures of the Dumbbell Nebula Hα band



2a



2b

Fig. 2: 30 frame stacks of 10 sec exposures of the Dumbbell Nebula Hα band with EM gain off (2a) and EM gain set at 200 (2b)

3a

3b

Fig. 3: The Omega Nebula Hα band stacked conventionally (3a) and drizzled (3b)

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Galaxies

M31: The Andromeda Nebula, our neighbour galaxy at a distance of approximately 2 Mio. lightyears. On the right side the dwarf galaxy M32.

(432 mm F/6; RGB 100 x 10 sec each)

M64: The Black Eye Galaxy at a distance of 24 Mio. lightyears in Coma Berenices. The large dust clouds near the centre are most likely remnants of a galactic collision.

(1,200 mm F/6; LRGB, L 40 x 20 sec, RGB 20 x 20 sec each)

M33: The Triangulum Galaxy, the third big galaxy of the local group, distance about 3 Mio. lightyears. M33 contains a large number of galactic nebulas (red) and populations of young hot stars (blue).

(432 mm F/6; LRGB, L 200 x 20 sec, RGB 50 x 20 sec each)

M66: Member of the Leo Galaxy Triplet at a distance of 36 Mio. lightyears, a barred spiral galaxy.

(1,200 mm F/6; LRGB, L 40 x 20 sec, RGB 20 x 20 sec each)

M51: The Whirlpool Galaxy, located in Canes Venatici, a typical spiral galaxy at a distance of 31 Mio. lightyears. One of the arms is deformed by the gravitation of its neighbour galaxy NGC 5195.

(1,200 mm F/6; RGB 30 x 20 sec each)

M82: An irregular starburst galaxy in Ursa Major at a distance of 12 Mio. lightyears. The structure is due to an almost collision with its neighbour M81.

(1,200 mm F/6; RGB 30 x 20 sec each)

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Globular Clusters

M13: One of the brightest globular clusters of the northern hemisphere, located in Hercules at a distance of 25,000 lightyears. In the left upper corner the distant galaxy NGC 6207 (46 Mio. lightyears).

(432 mm F/6; RGB 50 x 10 sec each)

Close up of M13.

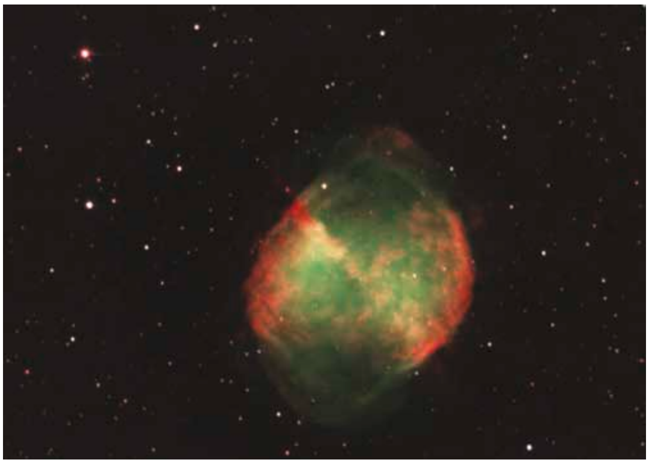
(1,200 mm F/6; LRGB, L 250 x 2 sec, RGB 50 x 10 sec each)

Reflection Nebulas

NGC 7023: The Iris Nebula in Cepheus, a huge dust cloud at a distance of 1,300 lightyears, illuminated by a single bright star.

(1,200 mm F/6; LRGB, L 100 x 20 sec, RGB 50 x 20 sec each)

Planetary Nebulas

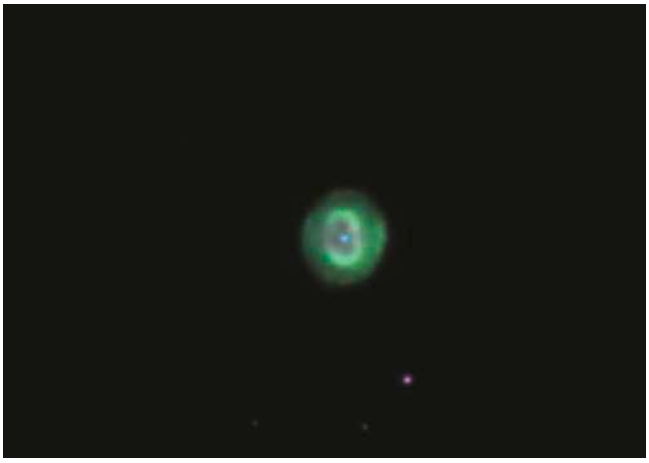


M27: The Dumbbell Nebula in Vulpecula at a distance of 1,300 lightyears. It is one of the largest and brightest planetary nebulas.

(1,200 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 50 x 20 sec each)

M57: The Ring Nebula in Lyra at a distance of 2,300 lightyears. The blue star in the centre of the nebula is the very hot white dwarf which remained after burn out of the original star.

(3,600 mm F/18; RGB 250 x 2 sec each)



NGC 7662: The Blue Snowball, a small planetary nebula in Andromeda at a distance of 5,000 lightyears.

(6,000 mm F/10; RGB 10% of 500 x 2 sec each)

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Galactic Nebulas

M8: The Lagoon Nebula in Saggitarius, a huge star formation area at a distance of 4,000 lightyears.

(432 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 25 x 20 sec each)

M17: The Omega Nebula, another hydrogen cloud in Sagittarius at a distance of 5,000 lightyears.

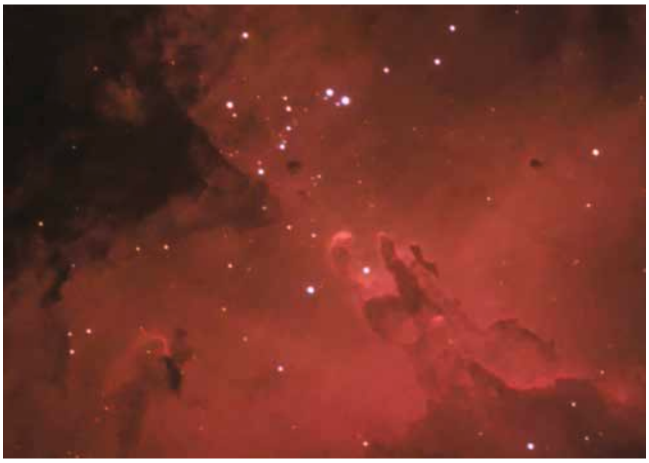
(432 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 50 x 20 sec each)

M16: The Eagle Nebula, also a star formation area in Serpens, distance 7,000 lightyears.

(432 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 50 x 30 sec each)

False colour picture of M17.

(432 mm F/6; narrowband, SII red, OIII green, Hα blue, 50 x 20 sec each)



Close up of the Pillars of Creation in M16. Here stars are born.

(1,400 mm F/8; RGB, Hα red 30 x 30 sec, OIII green 30 x 30 sec, blue dichroic blue 30 x 10 sec)

M42: The Orion Nebula, with only 1,300 lightyears distance the nearest star formation area.

(432 mm F/6, RGB 250 x 5 sec each)

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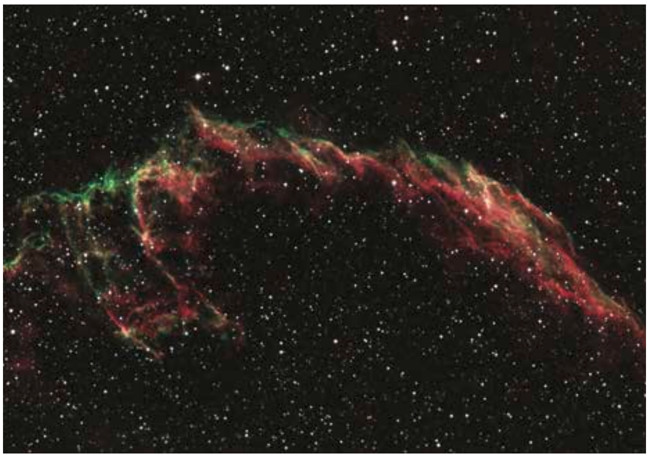
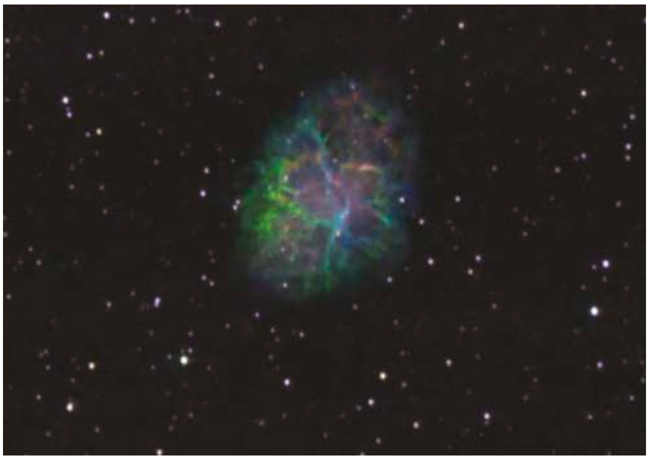
Super Nova Remnants

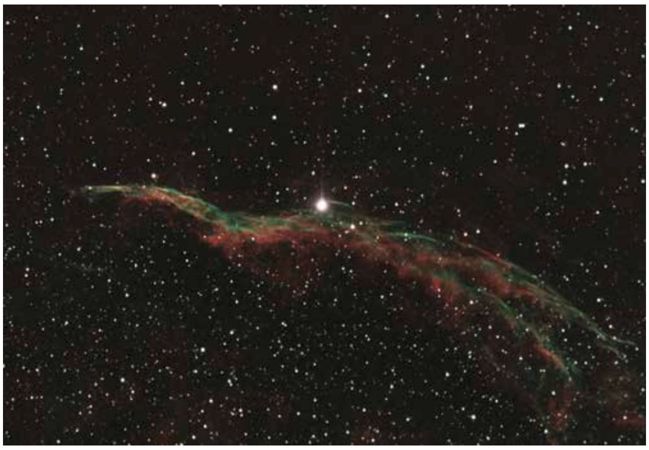
M1: The Crab Nebula in Taurus at a distance of 6,500 lightyears. It is one of the youngest objects in our galaxy, formed by a super nova observed by Chinese astronomers in the year 1054.
(1,200 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 50 x 20 sec each)



NGC 6992: The eastern part of the Veil Nebula.
(432 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 50 x 20 sec each)



False colour picture of M1.
(1,200 mm F/6; narrowband, SII red, Hα green, OIII blue, 50 x 20 sec each)



NGC 6960: The Veil Nebula (western part) in Cygnus at a distance of 2,000 lightyears has been formed by a super nova 10,000 years ago.
(432 mm F/6; narrowband, Hα red, OIII green, Hβ blue, 50 x 20 sec each)

Solar System

The planet Jupiter. On the left side the Jupiter moon Io.
(approx. 5, 000 mm F/25; RGB 250 x 0.1 sec each)

C/2006 W3: The comet Christensen passed earth in summer 2009.
(1, 200 mm F/5; RGB 20 x 30s each)