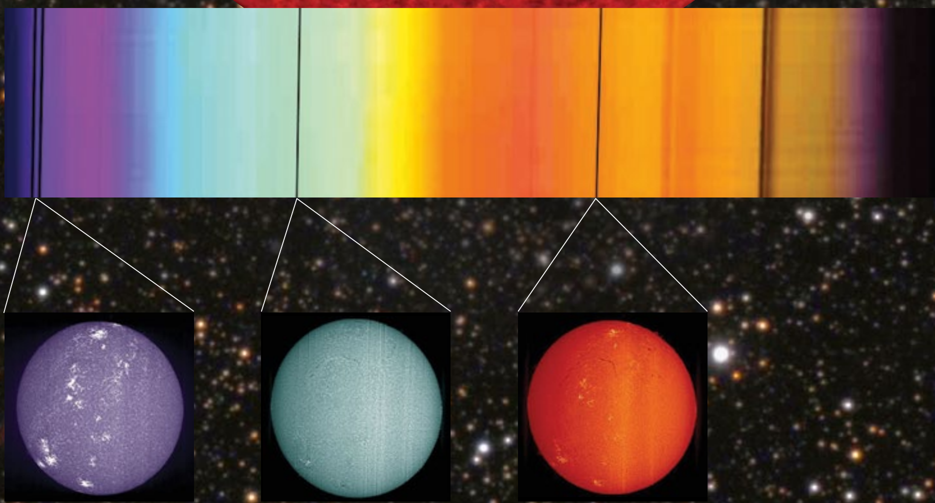
Ken M. Harrison

Imaging Sunlight Using a Digital Spectroheliograph



Patrick Moore's Practical Astronomy Series

The Patrick Moore Practical Astronomy Series

More information about this series at http://www.springer.com/series/3192

Imaging Sunlight Using a Digital Spectroheliograph

Ken M. Harrison

Springer

Ken M. Harrison
St Leonards, Vic, Australia

ISSN 1431-9756 ISSN 2197-6562 (electronic)
The Patrick Moore Practical Astronomy Series
ISBN 978-3-319-24872-1 ISBN 978-3-319-24874-5 (eBook)
DOI 10.1007/978-3-319-24874-5

Library of Congress Control Number: 2016937360

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

Dedicated to Fred Nall Veio

He kept the dream alive.

In Memory of

Walter Koch (Swisswalter)

5 Jan 1954—27 July 2015

“Only stardust in the wind”

Preface

Amateur astronomers have always been active solar observers. The recent advent of specialized narrowband solar telescopes such as the instruments from Coronado and Lunt has opened up the opportunity of observing and imaging the Sun in Hα and CaK wavelengths. Some of the images produced by solar imagers are of excellent quality and can stand comparison with those taken by professional observatories only a few years ago.

Moving from the traditional "white light" observation of sunspots and surface granulation to this exciting frontier of filaments and prominences, Ellerman bombs and flares unfortunately are still an expensive route to follow. The basic "cost of entry" to the Hα arena is in the $1000 plus range.

In the opening chapter of this book, we will follow the early work of the nineteenth-century amateurs and the introduction of photography to solar imaging before discussing the current designs of safe filters available to the amateur.

In Chap. 3, we review the nature of the Sun, our nearest star, and the varied solar features of interest which are regularly targeted by the imager. We will also provide comprehensive comparisons of the commercial filters and their benefits. Moving from the arena of solar filters, we consider the solar spectrum and the scientific benefits which can be obtained by imaging and recording detail in the spectrum.

This introduction to the solar spectrum then leads on to a parallel and, in my opinion, a more versatile and cost-effective solution to the traditional solar filters—the spectroheliograph (SHG). This instrument, invented in 1890 and further refined for visual observation in the 1920s, has long been the province of the hard-core DIY enthusiasts with avid talk about Anderson prisms and nodding mirrors and secondary optics like heliostats, siderostats, and cœlostats and other such large instruments taking up the whole backyard.

Fred Nall Veio has been championing the spectrohelioscope (SHS) for the past 50 years and has assisted many amateurs to build their own instrument. Without his continued dedication, this instrument and the opportunities it affords the amateur community could well have been lost to posterity.

A significant breakthrough occurred in the early 2000s when the early digital cameras were applied to the SHG. This innovation and the development of supporting software have reinvigorated the interest in the instrument and led the way to even more exciting designs and outstanding results. The concluding chapters cover the design and construction of the digital SHG illustrated with examples of instruments being used around the world, finishing with some details of the spectrohelioscope which will be of interest to the dedicated DIY amateur looking for a challenge.

As we will see, the images produced by today's SHGs are not yet achieving results at the quality standards of the cutting-edge narrowband filters, but it's just a matter of time before the software matures to further refine the images and show the full potential, at any chosen wavelength, of the digital SHG.

This is the story of the digital SHG, being written and continuously updated by amateurs around the globe—following in Fred's footsteps.

St. Leonards, Vic, Australia Ken M. Harrison

Acknowledgments

Many amateurs around the world have contributed their work to make this book as comprehensive as it is. I thank all those who have allowed me permission to use their illustrations and other materials.

I must mention specifically André Rondi, Philippe Rousselle, Daniel Defourneau, Jean-Jacques Poupeau, and Wah-Heung Yeun. This dedicated group of amateurs has led the way in the ongoing development of the digital SHG, and without their ongoing efforts, we would not be achieving the results we see today.

The active imagers on the Solar Chat forum have been especially supportive in allowing the use of their solar images.

I would also like express my deep appreciation to Fred Nall Veio for keeping the dream alive.

Contents

Chapter 1

Brief History of Solar Observations

1.1 Introduction

Since the earliest times on record solar observing has been practiced throughout the world as a means of understanding the seasons; megalithic monuments like Stonehenge and the solar alignment of the access tunnels to the burial barrows (the passage tombs of Maes Howe and Newgrange immediately come to mind) stand as evidence of the importance of the Sun to our ancestors. Our lifestyle has been determined by the daily rising and setting of the Sun. The solar phenomena of total eclipses have influenced governments and counties worldwide—and unfortunately for some early astronomers who got their calculations wrong also cost them their heads. During the reign of Tchong-Kang in China, in 2155 BC two unfortunate mathematicians Ho and Hi failed to accurately predict a solar eclipse and were put to death for their negligence.

The first measurement of the size of the Earth was achieved by the early Greek astronomer Eratosthenes in 290 BC just by observing the different altitude of the sun from different locations. The Chinese records show that naked eye sunspot groups have been observed for thousands of years. In the Western world, meanwhile, the main item of note was the publication of Copernicus' famous De Revolutionibus in the mid 1500s, stating that "in the center of everything the sun must reside; in the most beautiful temple created by God, there is the place that which awaits him where he can give light to all the planets".

For thousands of years, these naked eye observations and the deductions made from them satisfied the needs of the time, but the invention of the telescope from 1608 to 1610 was to change our perception of the Sun forever.

K.M. Harrison, *Imaging Sunlight Using a Digital Spectroheliograph*,
The Patrick Moore Practical Astronomy Series, DOI 10.1007/978-3-319-24874-5_1

1.1.1 Early Telescopic Observations

White light telescopic observations of the Sun have been conducted since the time of Galileo. Galileo Galilei (1564–1642) and his early contemporary observers were already aware of sunspots. Sometimes through smoke or haze they could be observed by the naked eye; the Chinese had been recording such sunspots for almost 2000 years but had no idea of their real origin, most of the observations being attributed to transits of Venus or Mercury or some other body in the solar system. This probably sounds strange with the benefit of hindsight based on our understanding of today, when scientists know that solar transit (where the disk of a planet appears to move across the surface of the Sun) of either of the inner planets only lasts a few hours whereas naked eye sunspots were visible for a few days.

Even the earliest telescopes were able to reveal that the sunspots were actually visible dark markings on the solar surface which rotated with the Sun. Galileo wrote in 1612:

> "Having made repeated observations I am at last convinced that the spots are objects close to the surface of the solar globe, where they are continually being produced and then dissolved, some quickly and some slowly; also that they are carried round the Sun by its rotation, which is completed in a period of about one lunar month. This is an occurrence of the first importance in itself, and still greater in its implications".

At a time when the Catholic Church would have everyone believe that the Earth was the center of all things and that everything revolved around it—this was pretty dangerous stuff. When Galileo reported he had observed the moons of Jupiter in 1610, then later the phases of Venus in 1613—"Venus imitates the aspects of the moon", the evidence for the old Ptolemaic earth scheme of things was becoming quickly untenable.

For the next few years the solar disk was regularly explored by telescope and it was quickly established that the outer edge of the solar disk appeared darker than the center of the disk. Sunspots were being recorded in sufficient detail to show the darker umbra and lighter penumbra regions and Galileo even recognized the slightly brighter surface areas near sunspot groups, giving them the name *faculae*, meaning "little torch" in Latin. Galileo also measured the brightness of the sunspots. He determined that they were not as dark as the moon shadows but actually as bright as a full moon—only appearing dark on the solar disk due to the extreme brilliance of the surrounding surface. The rotational period of the Sun, and even the approximate inclination of the axis were quickly established, all within a few short years. Such was the power of the new instrument to clearly see what had previously been undistinguishable, and to allow for new interpretations based on observation.

1.1.2 Solar Eclipses

The 5° inclination of the moon's orbit, combined with the Earth's movement around the Sun, means that the moon can sometimes obstruct the view of the disk of the Sun from the perspective of observers on the Earth. When this happens we have a solar eclipse. There are at least two eclipses visible from some part of the Earth every year. Depending on the moon's distance and the alignment of the lunar orbital plane, the eclipse can be partial, where the moon only covers a small amount of the Sun, or total. When the moon is further from the Earth, at lunar apogee, the apparent diameter of the moon is less than the Sun and gives rise to annular eclipses where a broad ring of the Sun is left visible. At other times when the moon is closer to the Earth, or lunar perigee, the moon can appear to be larger than the solar disk and gives us the spectacular total solar eclipse. A total eclipse can have a duration of as long as 7½ min. At this time the shadow of the moon is always less than 270 km wide traveling at a speed of at least 34 km/min across the Earth's surface.

Astronomers therefore have to plan and organize their travel plans to be in the best location to view a total eclipse, and hope the weather will be kind to them. In the past many total eclipse teams were met with almost insurmountable difficulties; war and shipwrecks were not uncommon obstacles to be overcome. Even when the observers were lucky with the weather, each eclipse seemed to raise more problems than it answered.

Captain Stanyan, observing the total eclipse of May 1706 from Bern, Switzerland is credited with the first recorded observation of the solar "atmosphere". He reported, after watching the Sun emerge from the eclipse "was proceeded by a Blood red streak of Light, from its Left Limb; which continued not longer than 6 or 7 Seconds of Time; then part of the Sun's Disk appeared…". The Astronomer Royal, John Flamsteed (1646–1719), inferred that rather than being an observation of the solar atmosphere, it proved the existence of a lunar atmosphere. Edmund Halley (1656–1742) (of Comet Halley fame), observing the 1715 total eclipse from London, documented not only the streamers radiating from behind the moon—its corona—but also a "long and very narrow Streak of dusky but strong Red Light seemed to color the dark edge of the Moon…". These are what we now know as solar prominences. Again the streamers and "red flames" were attributed to either the lunar or the Earth's atmosphere rather than to the Sun. It's worth noting that if every total eclipse could have been observed between 1610 and 1800 the total duration would have been approximately 400 min, just over 6½ h over a period close to 200 years. Not a lot of time to record the details of the nebulous observed atmosphere!

Alexander Wilson (1714–1786), observing the Sun from Glasgow, Scotland, got further than most eclipse observers of the Sun when he noted that the shape of a circular sunspot penumbra appeared distorted when viewed close to the limb. From this he inferred that the sunspot formed a depression in the surrounding surface, subsequently called the Wilson effect.

Barring these observations, there were no further significant solar discoveries made until the nineteenth century. It wasn't until the 1860s that the actual cause of the red flames that had been observed at various times was finally established by Norman Lockyer (1836–1920) using an early spectroscope. Advances in the scientific understanding of sunspots is addressed in the next section.

1.1.3 The Sunspot Cycle

By noting the visibility of sunspot groups, the longer term 11-year solar sunspot cycle was determined by Heinrich Schwabe (1789–1875). Working from the attic of his home in Dessau, Schwabe had started to observe and record sunspots in 1825. He found that in some years, such as 1828, there were so many sunspots it became difficult to keep track of them. The sunspot numbers began to decline and then rose again to a maximum in 1837. By 1843, after some 17 years of observations, he had gathered enough data to convince himself that the numbers of visible sunspots was showing a pattern of a decade or so between the maxima. He predicted that the next sunspot maximum would occur in 1849 and drop to a minimum some 5 years later. His ongoing results were published annually and confirmed the prediction.

September 1st 1859 proved to be an exciting day for the Victorian solar astronomer Richard Carrington (1826–1875) for reasons related to solar activity. Carrington had been employed as an observer at the Durham Observatory and observed the Sun for many years before joining the Harvard College Observatory eclipse party in 1851. That year's eclipse was visible in Sweden and Carrington made observations of both the corona and the elusive "red flames" during totality. He was enthralled by the event. Was there a connection between the sunspots he had been observing and these red flames? He felt there was, but confirmation had to wait a bit longer. By 1852 Carrington had left Durham and established an observatory in Redhill, Surrey where he set up a 4½″ refractor on an equatorial mount with the initial intent of compiling an accurate catalogue of the positions of the northern stars.

His life was about to change; he heard about Schwabe's work and read that Rudolph Wolf (1816–1893) from the University of Bern had investigated previous records and had managed to extend the sunspot data back to early 1755. It now appeared that the average sunspot cycle was closer to 11.11 years. Carrington was also somewhat surprised to find that there was very little data available prior to that date. This could have been due to the lack of observers—or the lack of sunspots to record. He then visited the library of the Royal Astronomical Society in London to review the historical solar records, where to his amazement he found that the records showed a very casual approach to the subject. There was no fixed frame of reference for the rotational period of the Sun and little agreement on the solar axis of rotation. Carrington decided it would be his role in life to correct these deficiencies and set about organizing a disciplined regular observational project to gather and prepare accurate data on sunspots.

By projecting an enlarged image of the Sun onto a white board and using fine cross-wires at the eyepiece he was able to measure the position of the various sunspots on the solar disk, and also by determining the time it took for the sunspot to drift across the crosswire its approximate size. This became his daily task for the next 11 years.

The historical data showed that the Sun's rotation could be anywhere from 25 to 28 days, and Carrington was determined to find an accurate answer. He assumed that the sunspots were carried along lines of latitude on the solar surface but did not know if the sunspots themselves moved on the surface, like leaves on the surface of a pond. By 1858 Carrington finally realized what was happening: the Sun didn't rotate as a solid body it showed differential rotation, rotating faster at the equator than at the poles. At the equator the rotation had a period of 25 days whereas at higher latitudes it was 28 days, with an average of 27 days. He also noted that at the beginning of a solar cycle the sunspots appeared at higher latitudes then as more spots became visible they were found closer to the equator. This was later confirmed by Gustav Sporer (1822–1895) and become known as Sporer's law. We now recognize it as the Butterfly diagram of the solar cycle (see Chap. 3 for more).

On the morning of the 1st September 1859, Carrington was observing the solar disk as usual and was busy admiring one of the largest sunspot group he had seen, this group extended almost one tenth the solar diameter. Without warning two extremely bright points of light suddenly appeared "*as bright as lightning*", these brightened even further and became kidney shaped before fading and drifting across the sunspot to disappear some 5 min later. Never had such an occurrence been recorded before. As he continued to observe the sunspot group returned to a more normal appearance. He had just observed a spectacular solar flare which resulted in the most dynamic magnetic storm and Aurora activity ever seen over the next few nights.

The scientific community now had some proof that solar activity could and did impact on the Earth's magnetic field.

Some years before, in 1842, General Edward Sabine (1788–1883) had established one of the first geomagnetic observatories in the world at the Kew Observatory in London. The intent was to measure and record magnetic disturbances, thereby confirming the relationship between magnetic activity and the often seen Aurora. Also at the Kew Observatory, following John Herschel's (1792–1871) pioneering work in photography, Sabine managed to get Warren de la Rue (1815–1889) to invest both his time and money in building a photoheliograph—a specialized telescope with the sole purpose of imaging the Solar surface daily. This refractor type instrument had an aperture of 3.4″ and 50″ focal length and was built by Ross of London. The design included a built-in enlarging lens to produce a final solar image of 12″ on a colloidal wet photographic plate. It was hoped that the images obtained would supplement the data being collected on the magnetic variations and confirm these were in some way connected to the sunspots. Although Kew observatory had not obtained any photographic or visual record of the flare, the magnetic equipment quickly confirmed the sheer scale of the disruption. A magnetic storm of the first degree had just occurred.

The magnitude of the solar flare was enormous and of such significance that it is still referred to as the Carrington super flare or Carrington event.

Carrington also developed the "Carrington rotation"; a system for comparing locations on the Sun over a period of time, thereby allowing sunspots to be identified upon their return after a solar revolution. It is based on a rotational period of 27.2753 days and the Carrington Rotation Number starts from November 9, 1853.

In 1860 De la Rue temporarily relocated the photoheliograph to Rivabellosa, Spain to attempt the imaging of the solar eclipse. He was successful in recording the first images of the solar chromosphere and finally demonstrated that the chromosphere was part of the solar atmosphere and not associated with the moon or the Earth's atmosphere. Similar confirmation images were obtained by Father Angelo Secchi (1818–1878) also observing from Spain. The Kew photoheliograph continued to take daily solar images up to the late 1890s.

As the nineteenth century progressed, other active solar observers like Herschel, Nasmyth, Huggins, Lockyer, Dawes, Wilson, Langley and Young all contributed to the growing knowledge and understanding of the nature of the Sun. It was the birth of solar studies in earnest. This is the period when the texture of the Sun's surface under low magnification was likened to rough drawing paper or curdled milk by the American Charles Young (1834–1908); nowadays we would call this the flocculi network. At higher magnification and steady seeing conditions, this network starts to resolve itself into the granulation, a term first used by William Dawes (1762–1836). These "grains", first noted by James Nasmyth (1808–1890) in 1861 who described them as "willow-leaves", were said to form a "sort of blanket-work formed by the interweaving of such filaments". Secchi thought them to be much smaller and compared them to rice-grains. Young also commented that some surface structures which appeared as "bits of straw" lying roughly parallel to each other, were sometimes noted in and around the penumbral regions of sunspots. The faculae recorded by Galileo were recorded as "looking much like the flecks of foam which mark the surface of a stream below a waterfall". From being an afterthought of astronomers, the Sun now had their full attention, and was inspiring flights of fancy as well as increasing the astronomical community's knowledge.

1.1.4 Photography

While the astronomers at Kew continued their solar photography, the lack of reliable and easy to use photographic material hampered the amateur. The original Daguerreotype (1839) and later wet colloidal glass plates (1850), although very popular, demanded care and attention not to mention very long exposure times. The competitive photographic method developed in 1841 by Fox Talbot (1800–1877) where a transparent paper negative was exposed, developed in silver nitrate, and then contact printed on salt-treated paper to produce a final print was still poorly accepted, even although Talbot's process allowed a single negative to produce multiple prints.

All this was to change in 1880 when gelatine replaced the old colloidal mixture and the Dry Plate Process was introduced. This new process allowed greater flexibility for the user and the short exposure times, seconds instead of minutes, became the catalyst for further camera development. Fast leaf shutters, allowing exposures of 1/5000 s and much improved multiple element lenses were quickly brought to the market. George Eastman (1854–1932) took the popular camera to the next stage with the release of his first mass market Kodak "you press the button, we do the rest" camera in 1890. The Kodak camera made use of a length of rolled flexible film based on a celluloid base coated with silver bromide. This film produced the negative from which multiple image prints could be produced. The success of this film based technology was to go on with improvements to sensitivity and the advent of color film to support the whole of the photographic industry for the next hundred years, only to be superseded in the twenty-first century by the introduction of the digital CCD technology. It is what allowed amateurs to step up their pursuit of solar viewing even further into the realm of imaging.

The invention and adoption of the spectroscope by chemists and astronomers in the mid 1800s added another dimension to the solar investigations, and the work of these early pioneers is discussed later in Chap. 4. The next chapter, however, focuses on the here-and-now of observing the Sun—and how to do it safely.

Further Reading

Clerke, A.M.: A Popular History of Astronomy. Adam & Charles Black (1887)
Young, C.A.: The Sun, Kegan Paul, Trench & Co. (1882)
Clark, S.: The Sun Kings, Princetown University Press, (2007)
Baatz, W.: Photography: A concise history, Laurence King (1999)

Chapter 2

Safe Filters for Solar Imaging

Now that a brief history of solar observing has been given, we are almost ready to move on to the meat of solar observation. First, however, tools must be discussed. This is of great importance for an amateur's outcomes, and it is a safety issue as well. Imaging the Sun with safety in various wavelengths and bandwidths has evolved substantially since the first attempts in the 1800s, and now requires the application of some very precise filter coating technologies. These sophisticated filter construction requirements can lead to expensive solar telescope designs.

Remember at all times, observing/imaging the Sun with any optical aid can be dangerous and can cause severe eye damage. With the proper application of safe filters the imaging of the solar features can be a very safe, rewarding and satisfying pastime. The solar surface presents one of the few dynamic targets in amateur astronomy. The recorded detail can change within minutes, making the task even more challenging, however the excitement of imaging detail like prominences lifting off from the solar surface or the explosions of Ellerman bombs make it all worthwhile.

Over the years solar observers have tried many different solutions to the problem of reducing the solar energy to safe levels for viewing. Some of these solutions were found to be better than others. For instance, notice in this section that welding glass and exposed photographic film don't get mentioned. These materials are not suitable for use by the solar imager and should not be considered at any time, though they have in the past been adopted as methods for visual observers of solar eclipses. This path is not recommended!

The following section reviews some of the significant developments in filter designs for white light and narrowband applications. The current commercial versions of some of these filter designs are detailed in Chap. 3 where the use of the various filters for imaging of the Sun is discussed in detail.

K.M. Harrison, *Imaging Sunlight Using a Digital Spectroheliograph*,
The Patrick Moore Practical Astronomy Series, DOI 10.1007/978-3-319-24874-5_2

2.1 Glass Filters

Colored glass filters have been used in photography and astronomy for the past hundred years. In that time they have been successfully deployed by generations of amateurs to image all sorts of astronomical objects. The early solar observers used smoked glass filters made by holding a plain glass plate over a smoky candle in an attempt to reduce the intensity of the sunlight. Later the use of dark green supposedly solar eyepiece filters became popular. These were intended to be used with small refractors or in conjunction with a Herschel Solar wedge. Unfortunately these are extremely dangerous. There are many reported incidents where the "solar" eyepiece filter has cracked due to the intense heat close to the focus of the telescope. If you do come across one of these small "solar" filters—sometimes unfortunately still found in the beginner's "First telescope" package as a "Sun filter," the recommended action is to take it in your right hand and throw it from a high cliff into the ocean where it can do no more damage — or smash it with a hammer. You will NEVER forgive yourself if you allow it to be used by a novice who subsequently suffers from irreparable eye damage. Nowadays all colored filters are used in conjunction with a full aperture solar film ND filter, a Herschel wedge or an ERF built into the optical train.

The Kodak Wratten number series for defining colored filters was developed by Fredrick Wratten (1840–1926) whose business was absorbed into Eastman's Kodak empire in 1912 and is still commonly used to specify the various filter transmission bandwidths. The Wratten numbering series is not self explanatory and the individual transmission curves need to be reviewed for each application.

Popular Wratten filters used by solar observers/imagers include:

Wratten 80A—Blue filter passing below 5200 Å
Wratten 40/58/60—Green filters similar to Continuum filters, peak transmission around 5300 Å
Wratten 24/25/29—Red filters blocking below 5750Å

Wratten filters are available in both gelatin and dyed in mass versions. Tiffen, Hoya and other manufacturers sell a wide range of quality glass photographic filters in various sizes to suit commercial cameras. Unfortunately the photographic filter sizes used in astronomical equipment are non standard and it can be difficult at times to find M48 threaded filters suitable for mounting into 2″ astronomical fittings. Also, the surface accuracy of the glass substrate is not necessarily of the highest quality. Most of these photographic filters are much less than the ¼ wave surface accuracy required in precision optics.

Schott manufacture a small but important range of dyed in the mass glass filters. Traditionally the red RG610 and RG620 glass have been used as energy rejection filters (ERF) in solar telescopes. Schott also manufacture some interesting special glasses, KG5 is a Schott Infra-red (IR) absorbing glass which can be used successfully in solar imaging to suppress any IR leakage from the narrowband filters. The standard sizes seem to be 25 mm diameter or 50×50 mm

2.2 Neutral Density (ND) and Optical Density (OD)

Originally for use with cameras and photographic film, the Neutral Density (ND) filters allowed the amount of light received by the film to be reduced without changing the aperture stop. The reduction in light transmission then allowed the photographer to have more control over the exposure time and depth of field. All ND filters absorb equally across the whole visible spectrum. The ND number of a Neutral Density filter defines the attenuation (reduction in transmission) and Optical Density (OD) of the filter. The ND and OD ratings are identical. ND numbers are additive i.e. a combination of a ND2 and an ND3 filter will be equal to a ND5 filter.

The optical density (OD) is related to the transmission by the following equation:

$$T = 10^{-OD} \times 100 = \text{percentage transmission.}$$

$$OD = -\log(T/100)$$

Example: If an ND 0.9 and a ND 2 filter are combined, what is the final percentage transmission?

$$ND = 0.9 + 2.0 = 2.9$$

$$T = 10^{-2.9} \times 100 = 0.00126 \times 100 = 0.126\%$$

ND/OD rating	Transmission (%)
ND 0.9 (OD 0.9)	12.5
ND 2.0 (OD 2.0)	1
ND 3.0 (OD 3.0)	0.098
ND 3.8 (OD 3.8)	0.016
ND 4.0 (OD 4.0)	0.01
ND 5.0 (OD 5.0)	0.001

In solar imaging the ND3.8 filter is regularly used for white light; ND5 is the recommended rating for extended visual observing.

All colored glass filters work by absorbing the light and energy from the wavelengths that are not transmitted. This energy absorption results in the filter heating up which can cause optical distortion or in extreme cases breakage. For solar work the modern multi-coated reflective filters are safer.

2.3 Multi-coated Filters

Modern developments in multi coating of glass filters has resulted in some very effective anti-reflection coatings (AR) being designed and made available. These AR coatings are now widely used on quality optical and astronomical lenses and associated equipment. The same techniques have also allowed narrow band dichroic filters, which block or transmit colors based on wavelength, to be constructed.

The popular Induced Transmission Filters (ITF) narrow band filters we see today are usually constructed by vacuum depositing a very thin, $\lambda/4$ thick metallic film on a glass substrate. Further dielectric films of $\lambda/4$ thickness and having specific design refractive indices are deposited to present an interference layer which suppresses and reflects all the wavelengths other than the design bandwidth. In these interference filters, light traveling from a lower index material will reflect off a higher index material; only light of a certain angle and wavelength will constructively interfere with the incoming beam and pass through the material, while all other light will destructively interfere and reflect off the material.

Soft coated multi-coated ITF filters are constructed by applying the sensitive coatings to two substrate plates. The mating edge circumference of each plate is cleared of coating and the sandwich is laminated together with moisture resistant epoxy glue. The glue gives a glass-epoxy-glass bond at the edge circumference to seal the filter and prevent moisture ingress. After final cutting to the finished size additional sealant may be added to the edge to further improve the moisture barrier and give added protection to prevent premature failure of the coatings. A similar process can be applied where the epoxy is only applied around the external edge. In this case there is no epoxy present in the optical path. This is the preferred construction of ITF filters used for solar work.

Hard spluttered filters have the multi-coated layers applied directly to one surface of the substrate and the choice of the film material and the application process provide a hard strong and durable external coating finish which can be cleaned without damage.

Typically the final coating thickness will be 10–20 μm and can take many hours to manufacture. The complexity, quality control, and manufacturing time adds to the cost of this filter design. The successful Baader D-ERF filter and the BelOptik Tri-ERF (CaK, Continuum, and Hα) are examples of this type of filter construction.

One limitation of all these dichroic interference filters is the limited field angle acceptance. As the angle of incidence increases through the filter the central wavelength of the bandpass will shift towards shorter wavelengths (i.e. towards bluer wavelengths).

2.4 White Light Solar Film Filters

Back in the 1970s Roger Tuthill (1919–2000) was the first to supply an aluminum coated Mylar filter, his “Solar Skreen”, to the astronomical market. This was well accepted by the amateur community as a safe solar white light filter. In a 1981 review by Dr. Chou of the School of Optometry, University of Waterloo, Toronto, it was favorably compared to the then-available aluminum coated premium Questar glass filter. Although providing a very safe ND level the final image quality was marred by the optical performance of the Mylar which presented a high degree of scatter due to internal strains and the grain structure of the material. The introduction of the Baader "AstroSolar" safety film in 1999 was a major step forward. This is a proprietary polymer film which has a surface accuracy of better than 1/8 wave and provides ND5 (neutral density factor 5) attenuation. The surfaces of the film are then ion implanted and coated with aluminum on both sides. Subsequent testing showed this solar film provided twice the optical quality of the aluminized Mylar and four times that of some inexpensive glass solar filters. It is available for DIY installation in ND3.8 (imaging) and ND5 (visual) variants and sheet sizes up to A3.

Only 1/10,000 of the incident light is allowed to pass through the filter. This complies with the international recommended solar protection level of ND3 or greater. The surface quality of the Baader film ensures that the solar detail visible and images recorded are not compromised. The final results will be limited by the seeing conditions and the optical quality of the instrument, but this remains a highly recommended solution.

There are other options, as well. The polymer/glass filters available from Thousand Oaks, JMB, Orion, Seymour and others are all safe to use. Check out the optical quality before making a final decision.

2.5 Herschel Solar Wedge

Invented by John Herschel in the 1800s, this solar filter externally looks like a star diagonal with an open section at the rear. Internally a plate of optical glass shaped in thickness to a wedge (a 10–30° taper) replaces the conventional reflective mirror and allows only 4 % of the incoming light to be reflected from the front surface and directed to the camera/eyepiece; the wedge shaped body then deflects the rest of the light and heat out of the rear of the diagonal housing. To reduce the final incident energy to safe levels the Herschel wedge MUST be used with a secondary neutral density (ND3) filter, positioned between the wedge and the camera/eyepiece. Likewise, any supplementary filters (i.e. Continuum etc.) must also be placed after the wedge to reduce the likelihood of thermal failure. Although this Herschel wedge is safe to use on all refractors, some manufactures do however, suggest limiting the telescope aperture to 125 mm or less to minimize any overheating. Most amateurs who have used the Herschel wedge believe the results are superior to any other design of white light solar filter. Baader, Lunt, Intes and others supply Herschel wedges in 1.25″ and 2″ sizes to fit most refractors.

2.6 Chromosphere Filters

The solar filters discussed so far only allow imaging of the photosphere. The structure of the Sun's atmosphere will be discussed in the next chapter, but those details are of no use without a proper filter. To image the upper regions of the solar