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Naked-eye Astronomy: Optics of the starry night skies

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ABSTRACT

The world at night offers a wealth of stimuli and opportunities as a resource for Optics education, at all age levels and from any (formal, non formal or informal) perspective. The starry sky and the urban nightscape provide a unique combination of pointlike sources with extremely different emission spectra and brightness levels on a generally darker, locally homogeneous background. This fact, combined with the particular characteristics of the human visual system under mesopic and scotopic conditions, provides a perfect setting for experiencing first-hand different optical phenomena of increasing levels of complexity: from the eye's point spread function to the luminance contrast threshold for source detection, from basic diffraction patterns to the intricate irradiance fluctuations due to atmospheric turbulence. Looking at the nightscape is also a perfect occasion to raise awareness on the increasing levels of light pollution associated to the misuse of public and private artificial light at night, to promote a sustainable use of lighting, and to take part in worldwide citizen science campaigns. Last but not least, night sky observing activities can be planned and developed following a very flexible schedule, allowing individual students to carry them out from home and sharing the results in the classroom as well as organizing social events and night star parties with the active engagement of families and groups of the local community. This contribution describes these possibilities and introduces some of the free resources available to put them in practice.

Classification fields: New Trends and Methods in Optical Education, Optics for All Ages, Outreach, Optics for Sustainable Development.

1. THE VISUAL NIGHTSCAPE

The world at night offers ample opportunities for experiencing many optical phenomena without resorting to complex optical equipment. Whereas in daytime the landscape is mostly composed of well lit extended scenes, the visual nightscape is dominated by pointlike sources shining on a generally much darker background. This feature, together with the fact that most of these sources are isolated from each other within the visual field, allow to observe with relative easiness many optical effects that in daytime are hard to notice, if possible at all.

In cloudless nights the celestial vault is full of stars. For all practical purposes the stars can be considered pointlike sources with almost-blackbody emission spectra. The greatest angular diameters of the stars, as seen from Earth and excluding the Sun, barely reach at most a few tens of milliarcseconds. Solar System planets are also visible, with distinctive brightnesses and hues and with variable angular diameters that in some cases may span several tens of arcseconds, depending on their sizes and distances to the Earth. The night sky also provides extended sources either very bright like the Moon or extremely faint like the Orion Nebula (M42) or the Andromeda Galaxy (M31). Besides these natural bodies artificial objects also contribute to the celestial nightscape: a swarm of artificial satellites of very different brightnesses can be observed naked-eye while running across the sky at appropriate times of the night (around dusk and dawn). The International Space Station (ISS) visible passes and the Iridium flares are particularly spectacular and eye-catching events.

To know in advance the stars and planets that can be observed naked-eye or with telescopes at any given time from any location one may use any of the several available free open source applications like Stellarium,¹ Cartes du Ciel,² or

SkyMap.³ The visual path of artificial satellites, including the ISS, can be known beforehand using some of these applications or visiting the comprehensive and continuously updated site Heavens-above.⁴

The terrestrial nightscape is full of sources of relatively small angular size and particular spectral features (Figure 1). The widespread extension of artificial lighting led to a profound change in the visual properties of the night.⁵ Streetlights and other artificial sources contribute with a variety of spectra ranging from the blackbody ones associated to incandescent lamps (conventional and halogenous) to the line spectra characteristic of gas discharge lamps (mainly high-pressure sodium vapor) and the more complex ones of fluorescent lamps and white-light solid state sources like phosphor-coated blue LEDs. Spreadsheets with the detailed spectra of the most common types of lamps are available at the NOAA's Earth Observation Group website.⁶



Figure 1: The waning crescent Moon, Venus and Jupiter shining above the city lights .

Using these sources many optical phenomena can be observed naked eye or with the aid of very simple optical components, thus providing a first-hand experience not mediated by unnecessarily hi-tech equipment. Besides, some of these effects can be successfully photographed and documented using relatively inexpensive compact cameras or smartphones. The nightscape is accessible for students from their homes on a daily basis, providing a flexible framework to schedule and develop individual as well as group projects. Due to the nature of the factors involved in stargazing (visual optics, light emission, atmospheric propagation, celestial mechanics...) the nightscape lends itself particularly well to carry out interdisciplinary projects. These activities are also instrumental for raising awareness on the detrimental effects of light pollution (on economy, the environment, public health and science)⁷⁻¹⁵ and to promote a culture of protection of the night sky as a part of the immaterial heritage of humankind, supporting that "an unpolluted night sky that allows the enjoyment and contemplation of the firmament should be considered an inalienable right equivalent to all other socio-cultural and environmental rights" according to the tenets of the La Palma Declaration.¹⁶ Some of the visual and optical phenomena that can be addressed using the nightscape as a resource are briefly summarized in the following sections.

2. THE SKY WITHIN OUR EYES

2.1. Learning about our visual system

Astronomers conventionally measure visual star brightness in "magnitudes", a logarithmic scale whose origins can be traced back to Hipparchus and that was later popularized by Ptolemy, who grouped the naked-eye visible stars into six classes, the brightest ones corresponding to the 1st magnitude and the faintest ones to the 6th. The modern brightness scale is due to Pogson (1856), and is defined in such a way that the visible flux of a 1st magnitude star is 100 times that

of a 6th magnitude one. Consequently, a difference of brightness of Δm magnitudes corresponds to a flux ratio of $10^{-(0.4 \cdot \Delta m)}$. An increase of one magnitude amounts to a decrease of about 2.51 times in flux. We use here apparent visual magnitudes, i.e., the magnitudes as observed from the Earth in contraposition to the absolute magnitudes which describe the brightness of the objects as they would appear if seen from a given standard distance (that for stars is taken as 10 parsecs, i.e. 32.6 light years). Bright celestial bodies can have apparent magnitudes smaller than 1, even negative (Table 1). Stars fainter than about the 6th magnitude usually require optical aids (binoculars, telescopes) to be seen. The number of stars increases dramatically with the magnitude (Table 2).

Table 1. Apparent visual magnitudes of several natural and artificial sky objects¹⁷

Object	Magnitude	Object	Magnitude
Sun	- 27	Sirius	- 1
Full Moon	- 13	Vega (α Lyr), Saturn (max)	0
Iridium flare (max)	- 9	Antares (α Sco)	1
ISS (max)	- 6	Polaris (α UMi)	2
Venus (max)	- 5	Cor Caroli (α CVn)	3
Jupiter (max), Mars (max)	- 3	Acubens (α Cnc)	4
Mercury (max)	- 2	Vesta (max), Uranus (max)	5

Table 2. Estimated number of stars brighter than a given apparent visual magnitude¹⁸

Apparent visual magnitude	Number of stars	Apparent visual magnitude	Number of stars
- 1.0	1	3.0	171
0.0	4	4.0	513
1.0	15	5.0	1602
2.0	48	6.0	4800

The naked-eye limiting magnitude (NELM) is the magnitude of the faintest stars that can be seen naked-eye under actual observation conditions. The NELM depends on several factors, among them the overall transparency of the atmosphere, the direction of observation (light from stars located far from the zenith traverses a thicker layer of atmosphere and becomes more attenuated by the combined effects of absorption and scattering), the background sky brightness due to moonlight and light pollution, and the visual conditions of the observer (dark adaptation, pupil size, refractive state, ametropia correction, best corrected visual acuity, etc). An emmetropic standard observer under clear, moonless, and light pollution free skies looking at the zenith should be able to perceive at least up to the 6th magnitude stars.

- Dark and light adaptation: Visually assessing the NELM and how it does change with time is a practical way to monitor the adaptation state of the eye. As it is well known, the human visual system can adapt itself to operate under a wide range of ambient luminances, spanning several orders of magnitude. A key element of such high dynamic range detection system is the presence of two kind of retinal imaging photoreceptors, the cones and the rods. At usual daytime (photopic) ambient luminances the rods are saturated whereas the cones provide spatially and color-resolved visual information to the brain. As the ambient luminance decreases at dusk and night, the cones lose progressively their ability to respond to the increasingly weaker light stimuli and the rods take the lead, allowing visual perception at very low (scotopic) light levels but at the cost of a smaller spatial resolution and the loss of color information. Dark adaptation, i.e., the process of adapting from photopic to scotopic light levels takes generally several tens of minutes; the reverse process is however much faster. The time evolution of the dark adaptation process can be monitored by leaving a well-lit room and going outdoors to watch the stars from a place free from the glare of street lamps: the progressive activation of the rod response allows to perceive fainter stars as time passes. Once the adaptation is reached for the average luminance level present outdoors, the limiting magnitude is mainly determined either by the sky background brightness (due to moonlight and/or light pollution) or by the detection threshold of the rod system (when gazing at the stars in moonless, no light polluted, pristine dark skies).

- **Luminance contrast:** The fact that the visual system responds to luminance contrast, rather than to luminance alone, can be easily checked by observing the night sky under light polluted skies or bright moonlight. After reaching dark adaptation at the level corresponding to the actual ambient luminance (that under light polluted skies may not reach the scotopic level but remain in the mesopic range), the limiting magnitude is determined by the brightness of the sky background. In that case our visual system is unable to see fainter objects not because there is not enough light from them reaching our eyes, but because their contrast with the background is below the contrast detection threshold. This can be seen with stars and also with extended objects such as the Milky Way, the Orion Nebula (M42) or the Andromeda Galaxy (M31) which are easily perceived naked eye under dark-skies but almost impossible to see from a typical urban setting.

- **Averted vision:** a striking demonstration of the fact that rods can operate with substantially smaller amounts of light than cones can be obtained under very dark skies by observing a faint celestial object, either pointlike or extended, whose brightness is below the cones response threshold but above the rods one. When looking directly at that object, i.e., when focusing it at the central fovea, the object disappears from view, whereas if looking at it somewhat off-axis it does reappear. This happens because the central fovea is almost exclusively composed of cones, unable to respond to such low light levels, while the density of rods increases as we move away from it. Now, the sudden perception of an object in the peripheral field instinctively triggers the reaction of looking at it directly with foveal fixation, and the object disappears again. A casual observer may be somewhat puzzled by this alternating cycle of appearances and disappearances, but controlling this reaction and consciously keeping peripheral fixation allows amateur astronomers to observe faint deep sky objects that would otherwise pass unnoticed. Experienced observers take full advantage of this technique of "averted vision" by imaging the objects on the maximum rod density region, located in the temporal retina about 20° away from the central fovea.

- **Colors: what our eyes miss at night.** Moonlit nightscapes are full of colors although our eyes are unable to perceive them because the ambient illumination levels are insufficient for the cones to work properly. However they are there, even in moonless nights only lit by starlight. An easy demonstration can be achieved using a small compact camera to photograph the nightscape under the light of the full Moon, with an exposure of several tens of seconds: the landscape features show the full colors we are used to see during daytime. The fact that this is actually a night shot is only suggested by the presence of stars in the sky (Figure 2).



Figure 2: The colors of the night. A full-color midnight landscape photographed using the light of the full Moon.

- **Eye aberrations:** The average human eye is not a perfect image-forming optical system, but it is affected to a bigger or lesser extent by several kinds of wave aberrations.¹⁹ Eye aberrations make the retinal image of a point source look like an intricate blurry spot, instead of the small and rotationally symmetric Airy pattern that would have a perfect eye. This phenomenon was already noticed by Galileo who discussing about the naked-eye observation of stars and planets

reported that "bright distant objects are not represented to us as simple and plain, but are festooned with adventitious and alien rays which are so long and dense that the bare bodies are shown as expanded ten, twenty, a hundred, or a thousand times as much as would appear to us if the little radiant crown which is not theirs were removed."²⁰ This "hairy" image, or eye's point spread function (PSF), is generally composed of a relatively small bright nucleus surrounded by less intense 'wings' that can span a visual field of several tens of arcminutes. Each eye has its own PSF. Eye aberrations are highly variable among the population, although the left and right eyes of the same person may show some degree of bilateral symmetry.

The PSF extent depends among other factors on the pupil size: bigger pupils generally give rise to wider PSFs, because the peripheral areas of the eye optics tend to be the more aberrated ones. As the pupil size decreases the PSF at first shrinks, but for sufficiently small pupils its size increases again due to diffraction (Figure 3). The PSF shape is difficult to perceive looking at extended objects in daytime, because the PSFs of all points add incoherently at the retina and the result is a slightly blurred extended image with somewhat decreased contrast (on average the blurring effect of the aberrations of a physiologically normal eye amounts to what would be produced by less than 0.25 diopters of myopy). To observe with ease the PSF shape and in particular the delicate structure of its wings we shall look at isolated bright point sources surrounded by a dark background. Nighttime is a perfect setting to do it. Suitable sources are bright stars like Sirius, Vega, Arcturus or Canopus, planets (especially Venus, Mars, Jupiter and Saturn), streetlamps several hundred meters away or even tiny LED indicators located at some distance in a darkened room.²¹



Figure 3. Left image: (Left column) The PSF of an actual eye for different pupil diameters, from 6 mm (top) to 1 mm (bottom) decreasing in steps of 1 mm. (Right column): the PSF of an ideal eye with no aberrations, for the same pupil sizes. Right image: (Top) An urban nightscape. (Bottom) The same nightscape as would be seen with the aberrated eye with a fully dilated pupil.

- **Intraocular scattering:** Isolated streetlights are also ideal sources to experience the effects of intraocular scattering. Light entering the eye becomes scattered by random irregularities of the refractive index distributions, including those due to localized small particles present in the ocular media. The scattered light does not reach the expected image point but spreads over a wide area of the retina. When looking at intense sources this effect is easily perceived as a bright halo surrounding the geometrical image of the source.

- **Visual acuity:** the starry sky can be used as a test chart to assess approximately the visual acuity, as it has been arguably done since ancient times.²² Suitable test objects are double stars like the 12-arcmin pair formed by Mizar (ζ UMa) and Alcor (80 UMa), open star clusters like the Pleiades (M45) or small detectable structures in the Moon such as the craters Copernicus and Aristarchus or the Mare Crisium (Figure 4).



Figure 4. Visual acuity tests. Left: the Big Dipper asterism in Ursa Major constellation. Mizar is the second star from the left in the handle of the dipper (image drawn using Stellarium). Right: Discernible features in the rising Full Moon (image courtesy of Teresa Mancebo).

- **Detecting peripheral events:** The night sky offers also a wide range of possibilities to check the ability of the eye for detecting light flashes or moving objects in the peripheral regions of the visual field (poor man's campimetry). Classical targets are "shooting stars" or meteors, the traces left at the atmosphere by the thermal and mechanical disintegration of small particles of cometary and asteroidal dust. Any typical night one can observe several meteors brighter than the third magnitude and, from time to time, much brighter events due to bigger-sized stones (bolids). The number of meteors is higher at some days of the year, when the Earth crosses regions close to the orbits of their parent bodies. This gives rise to "meteor showers" whose calendar and characteristics can be found in the International Meteor Organization (IMO) website.²³ Even during a meteor shower shooting stars are intrinsically random events, whose individual locations and times of occurrence cannot be predicted. If predictable events are required, one may resort to Iridium flares and the transits of artificial satellites of different brightnesses, especially the International Space Station, whose details can be known in advance.⁴

2.2. Learning about the atmosphere

- **Atmospheric extinction:** As already pointed out the naked-eye limiting magnitude (NELM) depends among other factors on the zenith distance of the line of sight, i.e. on the number of air masses traversed by light. A qualitative assessment of how much the atmosphere attenuates starlight for different air masses can be made from a dark site by determining the NELM at different angles above the horizon.

- **Star twinkling:** Atmospheric turbulence gives rise to eddies of different sizes with randomly distributed refractive indices due to the random fluctuations of air density. Light propagating through the turbulent atmosphere has different phase delays depending on the particular paths traveled by each ray. After propagation, these phase differences translate into irradiance fluctuations. At ground level this gives rise to caustic patterns qualitatively similar to those observed at the bottom of shallow waters in a sunny day, due to the ripples of the water surface. Since the eddies are carried by the winds present at different atmospheric heights, the ground level caustic pattern also moves transversally at considerable speed. This moving and fluctuating caustic pattern is what an observer notices as star twinkling (scintillation). If the air mass is big and the turbulence is strong, chromatic effects are clearly visible in bright stars, e.g. in Sirius near the horizon. According to conventional wisdom, planets do not twinkle: their angular span is wide enough for the rays coming from different points of their surfaces to traverse different atmospheric turbulent cells. Their different caustic patterns add randomly at ground level and the resulting irradiance fluctuations tend to cancel out. Irradiance fluctuations caused by horizontal-path light propagation from artificial sources can be easily observed at home in stormy nights on a dewy windowpane illuminated by a bright and distant streetlamp.

- **Night rainbows and halos:** Halos, rainbows (Moonbows) and other atmospheric refraction phenomena due to the interaction of moonlight with water drops, ice, dust and aerosols can also be observed at night, depending on the varying atmospheric conditions.

2.3. Observing basic optical phenomena

- **Interference and diffraction:** Streetlights are suitable sources to observe interference and diffraction phenomena, using the eyes as the only detector. High-pressure sodium vapor lamps have intense emissions in several interesting wavelengths; the LED sources used in traffic lights emit instead quasi-monochromatic light. Interference and diffraction effects can be observed by stopping the eye pupil using cards with appropriate holes or slits. Many students are surprised to see that observing Young fringes or Airy patterns does not require an optical bench. A wealth of diffraction patterns of different sizes can be obtained by carefully stopping the eye pupil by means of the eyelids, and additional patterns appear if the eyelashes superimpose over the pupil aperture. Textile fabrics produce interesting naked-eye diffraction effects (Figure 5).



Figure 5. Top left: An urban nightscape; Top right: The same nightscape as seen by a myopic eye; Bottom left: Diffraction effects looking naked eye at the nightscape through a window curtain; Bottom right: Idem, through a low frequency diffraction grating: note the almost monochromatic emission of the LED sources used in the traffic lights, unlike the more complex spectra of the high-pressure sodium vapor lamps.

- **Caustics:** A whole zoo of caustic patterns can be observed naked-eye and photographed with inexpensive cameras when the light propagates through water drops on spectacles or windowpanes.²⁴

- **The speed of light: looking at the past.** The vast interstellar distances provide a practicable way of looking directly at the past. Due to the finite speed of light we see the Moon as it was about 1.3 seconds ago, the Sun about eight minutes ago, the star Vega (α Lyr) about 25 years ago, the Pleiades (M45) about 400 years ago... and the Andromeda galaxy

(M31) as it was 2.5 million years ago. Coming back to Earth it is not difficult to grasp that we see the people around us as they were a few nanoseconds ago. Some students are puzzled when they realize that *everything* we see happened essentially on the past.

3. CITIZEN SCIENCE AND LIGHT POLLUTION AWARENESS

The widespread use of artificial lighting has radically altered the nightscape.⁵ Poorly designed lighting systems, both public and private, throw substantial amounts of light to the atmosphere in directions and wavelengths that are neither desired nor used at all for any practical purpose. In recent years sensible concerns have been raised among the scientific community about the problems caused by light pollution, the detrimental effects of the alteration of the natural levels of darkness due to the emissions of artificial light (Figure 6). Light pollution manifests itself in different forms, e.g., as increased levels of skyglow due to atmospheric scattering (Rayleigh and Mie), light trespass and glare. Artificial light at night has been shown to have unwanted side-effects on ecosystems and public health, along with the immediate consequences related to energy waste and greenhouse gas emissions.⁷⁻¹⁵ Studying light pollution and raising awareness about its effects are activities involving professional researchers of different scientific fields and amateur astronomers worldwide.²⁵

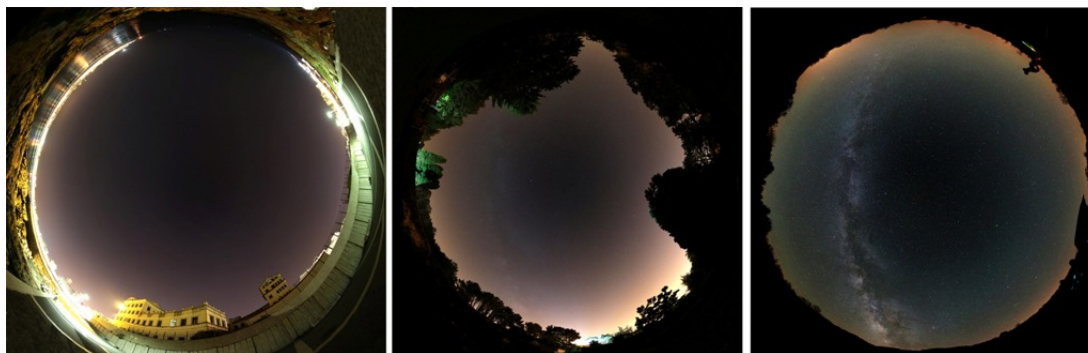


Figure 6. Light pollution and skyglow. The image at the left was taken near the center of a city with one-quarter million inhabitants (A Coruña). The next image was taken from a location eight km away from the city center. The right one was made at a rural area in the Eastern Mountains of Galicia, a place with almost pristine dark skies. They correspond approximately to the same region of the sky. The number of visible stars dramatically decreases as we approach the city center (Image courtesy of Oscar Blanco Varela).

Several kind of data can be used to estimate the light pollution levels at any location on Earth. Some of them are available from statistical sources (e.g. the number, kind, and distribution of street lamps, installed electric power, etc). More reliable data of the artificial light emissions in several spectral bands are gathered by dedicated satellites such as the Suomi NPP.²⁶ Models of light propagation and scattering through the atmosphere allow to estimate the contribution of these artificial emissions to the night sky brightness.⁷ Validating these models requires of an ample database of visual brightness measurements, something that can be done by estimating the NELM of several areas of the sky under reasonably controlled conditions from a big number of locations distributed throughout the Earth and through long periods of time. Reducing the unavoidable uncertainties associated to such kind of estimations requires in turn a high number of individual observations. Since NELM estimations can be made without the need of a long and specialized training period, this kind of research lends itself well to promote citizen science projects.

A relevant initiative in this field is GLOBE at Night,²⁷ a worldwide citizen science program to raise public awareness on the impacts of light pollution. Individuals and groups, teachers and families, as well as citizens at large no matter their academic qualifications are encouraged to participate, engaging in a self- and mutual education process and contributing at the same time useful data on the local brightness of the night sky, whose increase over the naturally expected levels is one of the most conspicuous manifestations of the light pollution problem. No sophisticated technical equipment is required to perform these measurements: the sky brightness is evaluated by means of the naked-eye limiting magnitude, although there is the possibility of uploading quantitative measurements obtained with some commercial

luminancimeters. GLOBE at Night is presently sponsored by the NOAO (US National Optical Astronomy Observatory), CADIAS (Centro de Apoyo a la Didáctica de la Astronomía, Chile) and the IDA (International Dark-Sky Association). In its first seven editions more than 83,000 measurements have been contributed by people from 115 countries, arguably making GLOBE at Night one of the most successful citizen science programs ever developed.

GLOBE at Night is structured in yearly editions held from January to May. Each edition is typically composed of several ten-days campaigns coincident with the periods around the New Moon in order to avoid significant contributions of moonlight to the overall sky brightness, something that would hinder the estimation of the NELM due to artificial sources. With the help of a series of specific materials available at its website (multilingual Teacher and Families Activity Packets, printable magnitude charts, additional resources for the "Dark Skies Rangers" program)²⁸ and a multilingual webapp to submit data²⁹ participants are asked to perform five easy steps: (i) Finding their latitude and longitude; (ii) finding the constellation to be used for the measurement, typically Orion, Leo or Crux, depending on the observer's location and the time of the year, and allowing some time for the eyes to become reasonably dark-adapted; (iii) matching their nighttime sky with one of the seven limiting-magnitude star charts provided to them; (iv) reporting the observation online, via the webapp and (v) comparing their observations with those of other people around the world available in real time in an interactive map viewer³⁰.

Despite the high variability of the local light pollution conditions, the huge amount of data accumulated are expected to provide useful information on the present levels of light pollution as well as some indications of their trends. A recently published study concluded that aggregated GLOBE at Night data could be used to track lighting changes worldwide.³¹

4. OPTICS AND SOCIAL ASTRONOMY: GETTING IN TOUCH WITH THE LOCAL COMMUNITY

Public sky observations and star parties -with or without telescopes- from open places in towns and neighborhoods are listed among the most popular science events. This kind of activities, that sometimes are accompanied by an outreach talk related to some hot topic in the field, usually bring together a wide intergenerational audience and arouse a considerable degree of interest.³² These social astronomy activities are also a privileged occasion for informal optics education. While naked-eye stargazing allows to address most of the topics described above, instrumental observing with the aid of binoculars or telescopes opens a wide range of possibilities to address the basics of imaging optics from a leisure time approach. Much is to be gained if such activities are organized in cooperation with the formal and informal groups active in the local community.³³

5. CONCLUSIONS

The nightscape is an optically rich environment that may be advantageously used as a freely available resource for Optics education at all levels and for all ages. Its unique combination of pointlike sources with extremely different emission spectra and brightnesses and a dark background allows the naked-eye observation of many interesting optical phenomena that would be difficult to see during daytime. Interacting with Astronomy and Vision Science, nighttime Optics lends itself to interdisciplinarity. Social astronomy activities developed in cooperation with the local community groups offer a natural way for addressing optical topics from a leisure-time approach.

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