Environmental Impact of Light Pollution and its Abatement

Special Report of the
Journal of The Royal Astronomical
Society of Canada

Special Issue "Environmental Impact of Light Pollution and its Abatement"

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President's Message

Welcome to our special supplement report, *Environmental Impact of Light Pollution and its Abatement*.

The Royal Astronomical Society of Canada (RASC) thanks and recognizes the funding support from the Canadian Periodical Fund at Canadian Heritage, which made this report possible. Special appreciation is given to the volunteers led by Robert Dick, Chair of the RASC Light-Pollution Abatement Committee, for their vital contributions.

The RASC is Canada's leading astronomy organization, bringing together more than 4,000 enthusiastic amateurs, educators, and professional members in every province of Canada. Our vision is to inspire curiosity in all people about the Universe, to share scientific knowledge, and to foster collaboration in astronomical pursuits.

Through this and future projects, it is our objective to work toward social and legislative change that will result in more responsible lighting practices in Canada; the ultimate goal being to preserve the nighttime environment for all to enjoy.

Clear skies,
Glenn Hawley, RASC President

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Canadian Publications Mail
Registration No. 09818
Canada Post:
Send address changes to 203 – 4920
Dundas St W, Toronto ON
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Post Publication Agreement No. 40069313

The *Journal* is a publication of The Royal Astronomical Society of Canada. Membership is open to anyone interested in astronomy.

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This project is supported by the Canadian Periodical Fund at Canadian Heritage.

Ce projet est financé par le Fonds du Canada pour les périodiques de Patrimoine canadien.

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We acknowledge the financial support of the Government of Canada through the Canada Periodical Fund (CPF) for our publishing activities.

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Prologue – JRASC-LPA

– Robert Dick

Chair RASC LPA Committee

This special issue presents a selection of articles covering a few diverse aspects of lighting and light-pollution abatement (LPA) with authoritative summaries.

One *Journal* issue is not enough to cover all the information that we feel is necessary for a good overview of the subject. However, due to space constraints, we had to edit both our list of topics and our articles down to fit this issue. We hope the range of topics in this sample will carry you out of your knowledge comfort zone and expose you to additional issues and information. Light Pollution (LP) is not an issue for only astronomers—it fundamentally changes the world—for good and ill.

Light is used to assist our vision, so understanding our eye is critical. Dr. Chou also explains some of the frustrating limits to our visual acuity in the face of LP—especially as we grow older. These exacerbate the impact of LP and reduce the benefits of artificial light at night (ALAN).

ALAN has more profound impact than the public is aware. Scotobiology provides a focus for understanding the biological and ecological effects of ALAN and helps place these effects into a broader context.

Our social policies are homocentric, so understanding the impact of ALAN on human health is critical in a debate on how we use light. Some readers may find Dr. Roberts' article on human health quite disturbing. It clearly summarizes the reason for our efforts to change the way we use ALAN.

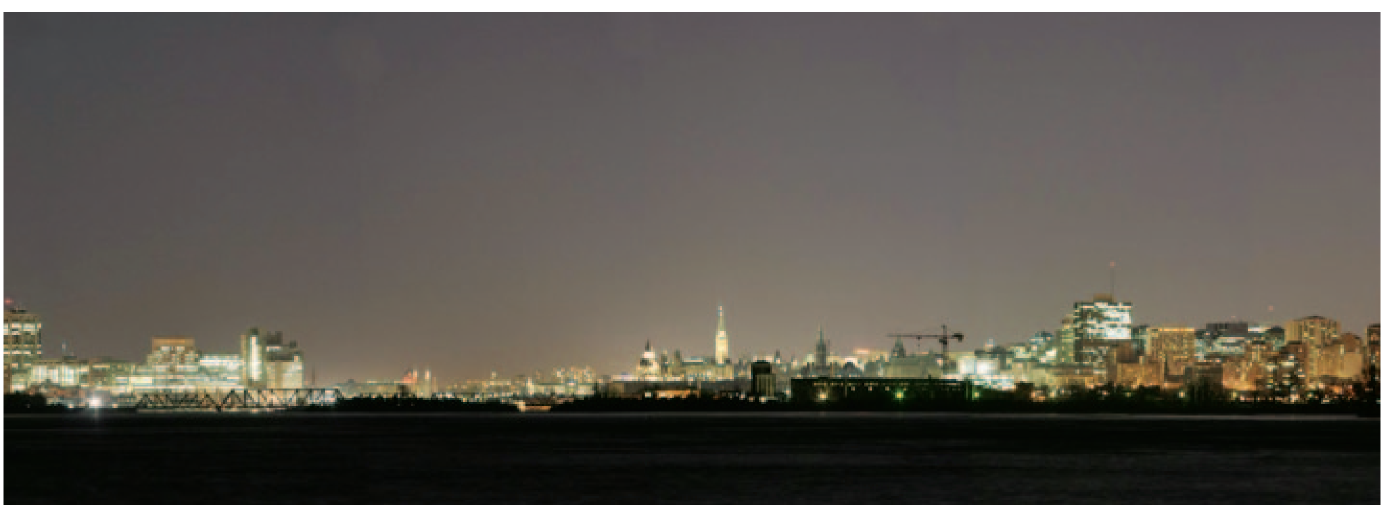
We can draw a lesson from the Roman Empire and the use of lead wine goblets. The reported lead poisoning may have been a contributing factor to the empire's decline. Will our society's use of ALAN be a similar factor contributing to our decline?

One of the main uses for outdoor lighting is for roadway illumination. There is a reason why street lighting is used, and Dr. Bullough's article presents the problem of roadway visibility from a practitioner's standpoint. Changes to roadway lighting must address these needs, while reducing its adverse impact on the environment.

New luminaires using LEDs are beginning to replace older fixtures, but these are not a panacea for LP. We hope you will find the article on LEDs to be an unbiased presentation on solid-state lighting—putting its properties into a more general context and highlighting the present pros and cons of LEDs.

A place or region that agrees to reduce sky glow is under constant pressure to revert to previous practice. Eposodic, or even continuous effort is needed to maintain the rate of improvement as outlined in Giguère's article. Light pollution is a challenge for all nations. Dr. Welch provides a global perspective on the efforts to reduce LP. History, culture, economics, and politics all play important roles in how the problem of ALAN can be addressed.

Additional information on these and other topics will be added to the RASC Web site (www.rasc.ca/lpa/tech/). It will not be a compendium of general information—there are many other Web sites for that. Rather we hope this site will contain novel and authoritative information to increase our understanding of light pollution to support and energize the debate.



Artificial light at night has become a symbol of our affluent society. This image evokes two emotions: one is the impressive display of activity and power, and the other is energy waste and a disregard for the natural night. In reducing light pollution, we must be conscious of both these perspectives (April 2008, R. Dick).

The Eye and Visual System: A Brief Introduction

– B. Ralph Chou

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Abstract

The purpose of this paper is to provide an introduction to the structure and function of the human eye and visual system as they relate to discussions around light-pollution abatement. It will be assumed that a normal adult human eye and visual system are being described.

Structure of the Eye

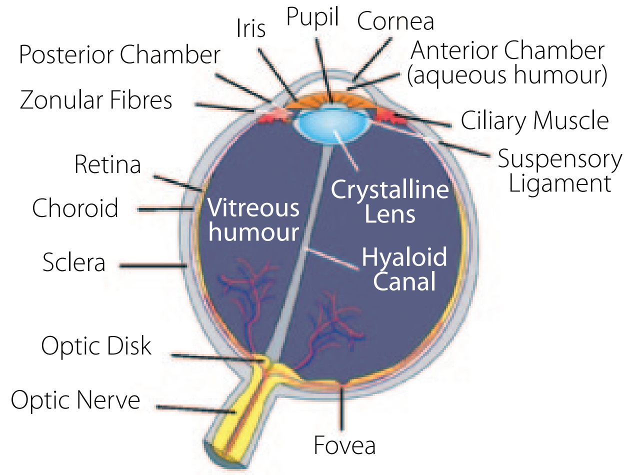

Figure 1 – Cross section of a right human eyeball as seen from above. This is a cut along the horizontal direction through the fovea. The optic nerve is on the nasal (left) side of the eyeball. Source: Wikipedia Schematic_diagram_of_the_human_eye_with_English_annotations.svg. Public domain.

The adult human eye is a roughly globular organ approximately 25 mm in diameter (Figure 1) with a tough outer coat (the sclera) composed of collagen fibres. Blood vessels (the choroid) line the inside of the sclera along with granules of melanin pigment that act as a light trap for light transmitted through the sclera. The retina covers the inside surface of the choroid and contains the light-sensitive photoreceptors and neural cells. A relatively clear avascular gel (the vitreous humour) fills the spherical interior to maintain the eyeball's shape.

Light enters the eye through the transparent cornea. The cornea is approximately 12 mm in diameter and is a complex structure about 540 μm thick at its centre. The front surface of the central cornea has a radius of curvature of about 7.8 mm and accounts for approximately 66% of the refractive power of the eye. The cornea flattens towards its periphery to about 700 μm thick at the edge, where it merges into the sclera.

Light continues through the anterior chamber and past the iris into the crystalline lens. The iris contains a smooth muscle ring (sphincter muscle) surrounding the pupil aperture, which acts to constrict the pupil. A set of radially oriented smooth-muscle fibres runs from the sphincter to the base of the iris. This dilator muscle opposes the sphincter muscle to open the pupil. The pupil can vary in size from 2 mm at full constriction to almost 8 mm at maximum dilation, depending on illuminance level in the environment.

The iris tissue may contain melanin pigment granules, which give the iris its colour. A blue iris contains no melanin and gets its colour from Tyndall scattering of light through the iris material. As the melanin content of the iris increases, the iris colour ranges from green to hazel to shades of brown.

The crystalline lens accounts for about 1/3 of the refractive power of the eye. The lens absorbs nutrients from the aqueous humour and continues to grow slowly throughout life. New lens fibres grow parallel to the lens capsule, extending radially along the front and back surfaces to meet other lens fibres along the optical axis of the lens. The intersections of the lens fibres are where early cortical cataracts may sometimes be observed in older individuals.

The crystalline lens is suspended in front of the vitreous body from thin fibres, the zonule of Zinn, that run from the equator of the capsule to the ciliary body (see Figure 1). Action of the ciliary muscle in the ciliary body changes the tension on the zonular fibres, allowing the lens to change its shape and thus its refractive power. In visual accommodation, the zonular tension is reduced, which allows the lens to bulge and increase its refractive power so that near objects come into focus on the retina with its light detection cells.

In the human eye, there are two distinct types of visual photoreceptor cells. The retina is therefore actually a duplex retina. The cones are elongated cells with relatively stubby cone-shaped outer segments. The rods are relatively thin elongated cells found everywhere in the retina except at the centre of the visual field of the eye (fovea centralis), where the highest concentration of cones is found (see Table 1). The concentration of rods increases rapidly outside the fovea to a maximum about 15 degrees away from the centre, then it decreases.

Table 1

Subdivision of the retina (from Polyak, 1941)

Retinal region	Outer Diameter (μm)*	Angular Diameter (degrees)*
Central fovea (no rods present)	50–75	0.17–0.24
Avascular fovea (no blood vessels)	400	1.4
Foveal pit	1500	5.2
Macula	3000	10
Near periphery	8500	29
Mid periphery	14500	50
Far periphery	40000	

**as measured from the centre of the fovea*

Overall, there are approximately 6 to 7 million cones and about 100 million rods in the eye. The individual cones show a preferential sensitivity to long-, medium-, or short-wavelength light, with the majority being most sensitive to either red or green light. The blue-sensitive cones are relatively sparse and almost absent from the fovea. Collectively, the cone retina has a spectral sensitivity curve that shows a maximum sensitivity at 555 nm. The cones function best at high illumination levels and are responsible for daylight (photopic) vision with fine resolution and colour vision.

Rods function best at low (scotopic) illumination levels; rod vision is characterized by its low-resolution black-and-white vision typically at night. The spectral sensitivity curve of rod vision has a peak at 505 nm. On an absolute scale, the rod sensitivity peak is about three orders of magnitude higher than the cone peak. Rhodopsin is the pigment associated with rods, and is structurally similar to carotenoids such as vitamin A. Cone pigments are less well understood, but thought to have a similar structure.

Although the general anatomy of the retina has been well documented since the time of Cajal (1892), it was left to the electrophysiological and other experimental techniques of the 20th century to elucidate the actual function of the various retinal cell populations.

One population of up to five different cell types (Schmidt *et al.*, 2011) is not used for vision. The intrinsically photosensitive retinal ganglion cells (ipRGCs) form large-scale networks that comprise about 1 to 2.5% of the retinal ganglion cells (Hattar *et al.*, 2002) and represent a third population of photosensitive cells. The neural networks supplied by the ipRGCs, rods, and cones make maximum use of the light reaching the retina. The spectral response of the ipRGCs is that of the photopigment melanopsin, which peaks between 460 and 484 nm. These cells respond much slower to light than the rods and cones, which also provide inputs to them. Although most photons pass by the ipRGCs to the rods and cones, only a single absorbed photon is needed for an ipRGC to signal the presence of light to the brain.

The ipRGCs are important in regulating pupil size in response to ambient lighting conditions and synchronizing circadian rhythms to the light/dark cycle with light-mediated regulation and suppression of melatonin release from the pineal gland. In humans lacking photoreceptors, ipRGCs appear to provide a rudimentary conscious visual awareness (Zaidi *et al.*, 2007). Schmidt *et al.*, (2011) provide an excellent review of what is known about the role of ipRGCs.

From Light to Vision

As much as 30% of the light entering the eye is scattered by ocular tissues and does not contribute to image formation at the retina, so the outer segments of the detector cells are surrounded by a pigment layer (retinal pigment epithelium) that acts as a light trap. When a photon of light is absorbed by a visual pigment molecule, the molecule undergoes a light-induced structural change (photoisomerization), which initiates an electrical signal that passes from the photoreceptor to the bipolar cells in the inner nuclear layer of the retina—ahead of the rods and cones. From the bipolar cell, the signal is passed to a retinal ganglion cell, a neural cell whose axon runs to the optic nerve and terminates in the brain at the lateral geniculate body. The neural signal travels from there to the occipital lobe of the brain to become a visual percept.

Each bipolar cell receives signals from several photoreceptors (Figure 2). The network of direct and indirect connections to the ganglion cells allows for basic visual processes such as contrast detection and enhancement, colour coding of cone signals, and detection of temporally varying signals to occur

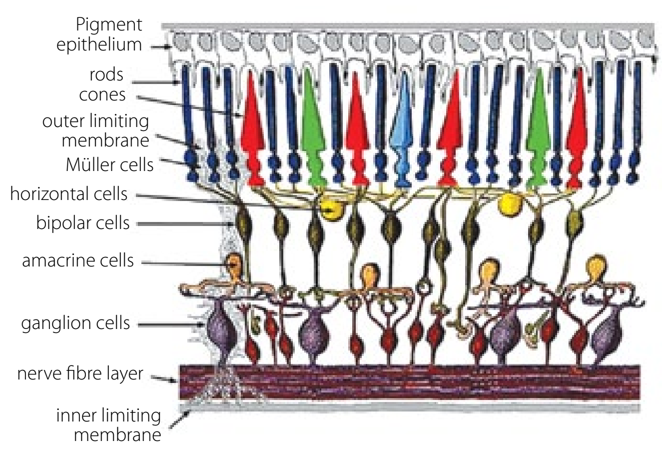

Figure 2 – Cross section of human retina. Public domain. Source: http://webvision.med.utah.edu/book/part-i-foundations/simple-anatomy-of-the-retina/ Accessed 2012 September 12

Table 2

Comparison of Day and Night Vision – Selected Characteristics

Characteristic	Day (Photopic) Vision	Night (Scotopic) Vision
Photoreceptor	Cones	Rods
Maximum Resolution	0.75 to 1.0′	10′
Colour vision	Yes	No
Peak of spectral sensitivity	555 nm	505 nm
Adaptation level	> 3 cd/m^2	< 0.01cd/m^2

within the retina. The output of more than 100 million photoreceptors emerges from the eye in a nerve that contains about one million individual nerve fibres. Only cone cells that are responsible for fine resolution and colour vision show one-to-one connections to bipolar and ganglion cells. Everywhere else, signal convergence is the rule.

Vision in Day and Night

The qualities of day and night vision are very different. Selected characteristics are compared in Table 2. Adaptation is the process by which the duplex retina "turns on" the photoreceptors most suited to the lighting conditions. Adaptation to bright light is relatively quick, but can be uncomfortable if the increase in illumination is abrupt, such as what happens when a bright light is shone into the eye in dim conditions. The discomfort is mostly due to the spasm-like action of the iris sphincter as it rapidly constricts the pupil. The sensation of dazzle fades as the rod cells exhaust their rhodopsin and stop responding to the bright light.

By contrast, dark adaptation is a slower process that takes as long as two hours for the rod retina to reach maximum sensitivity in absolute darkness (Bartlett, 1965). The actual time depends on the initial illumination level. As the light dims, the cones become less responsive, while the rods regenerate rhodopsin and start functioning. Because there are no rods in the fovea, vision in very dim lighting is eccentric, that is, one must look in a direction slightly to the side of an object of interest in order for it to be seen at all (averted vision). In most viewing conditions at night, there is enough light in the environment that true dark adaptation is never reached; the visual system is in a state of "mesopic" adaptation with a mix of rod and cone function.

It was noted earlier that up to 30% of the light that enters the eye does not contribute to image formation. Instead, this scattered light creates a veiling effect that reduces contrast in the retinal image. This is referred to as "glare." If the level of glare simply impairs one's ability to see details, it is referred to as disability glare. When the glare is sufficient to cause visual discomfort, it is called discomfort glare. Being flashed by high beams from an oncoming car while driving at night is an example of both discomfort and disability glare—the sudden increase in retinal illuminance feels uncomfortable and the scattered light in the eye makes it difficult to see the road ahead.

Fry and Alpern (1953) found that a glare source of illuminance E at the eye produced a veiling haze luminance proportional to $E / \theta^{2.5}$ where θ is the angle between the glare source and the visual axis. A bright source immediately next to the object of regard has a much greater effect on visibility of the object than one that is further away. Similarly, the amount of veiling glare depends on the angular size of the glare source.

Age-related Changes to the Eye and Vision

The pupil is largest in childhood and gets smaller with age. In children, the constricted pupil is typically 4 mm in diameter, while in the dark it is 7 mm or more. By the age of 60 years, most adults have constricted pupils of about 2 mm in diameter, which dilate to a typical maximum of 5 mm in the dark.

The crystalline lens continues to grow slowly throughout life, gradually becoming harder and more yellow at its nucleus (nuclear sclerosis). The increasing yellow colour of the lens helps to protect the retina from short wavelength light but also makes perception of shades of blue and green progressively more difficult. At the same time, hardening of the lens decreases the amount of accommodation; by the mid-40s most adults require reading glasses or bifocals to read comfortably.

The ageing eye becomes metabolically less efficient, so that regeneration of the photoreceptor pigments slows and the metabolic pumps are less able to keep the cornea and lens transparent. Gaffney *et al.*, (2012) reported that cone dark adaptation takes twice as long at age >70 years as at age 20 to 30 years. By the age of 50 years, most individuals show haze and opacities in the outer layers of the crystalline lens, the earliest signs of a cortical cataract. The cortical changes increase the veiling glare inside the eye, causing a progressive loss of visual acuity for targets with low to medium contrast, although standard high-contrast acuity remains near normal. In addition, early-life exposure of the retina to short wavelength UV and blue light is thought to contribute to the development of dry age-related macular degeneration.

Summary

The changes we observe in the ageing eye and visual system can cause deleterious changes in vision, especially under night-viewing conditions. Artificial light at night, especially from poorly designed street lighting and other light sources, may contribute to further degradation of vision due to the combined effects of altered spectral composition, unintended spatial distribution, and unwanted veiling glare. Finding the right balance between our need for light at night and the environmental constraints of providing that light, while minimizing its effect on human health, is a continuing challenge (Clark, 2005).

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Our eyes have adapted to bright daylight and faint nightlight. Isolated bright lights at night raise a conflict where the glare renders our night vision ineffective. As a result "more light" on one property results in "less visibility" over a wider area.

Scotobiology

– Robert Dick

Abstract

Scotobiology is the study of the biological need for periods of darkness. Unlike its antithesis "photobiology" (the biological need for light), scotobiology focuses on the benefits of minimal light and determining the limits for that light. This changes the perspective, if not the interpretation of the data.

For over a century, environmental studies have focused on how light makes a positive impact on nature. It helps plant growth, improves animal and human navigation, and it supports our 24/7 life style. Studies have shown that the illumination levels, spectra, and time of exposure impact all life forms. These data are being re-interpreted to show how artificial light at night (ALAN) affects our natural environment and alters animal behaviour. It also suggests lighting thresholds, timing, and spectra that can minimize its impact on our health.

Night and Evolution

The rotation of the Earth creates day and night—making it indigenous to our planet. The tilt of its axis causes the duration of daylight to seasonally vary from about 8.5 hours in our Canadian winter to 16 hours in our summer, and our atmosphere causes a protracted transition from day to night. These seasonal and atmospheric effects suggest that there is an inherent tolerance to ALAN beyond a few hours after sunset.

By chance, an ancient cosmic impact resulted in the Moon that now illuminates some of our nights, and has caused all life forms to evolve with a tolerance to monthly variations in nocturnal illumination between 0.002 Lux (starlight) to 0.27 Lux (full Moon)[1]. When compared to daylight (130,000 Lux), this variation seems insignificant; however scotobiology shows that wildlife is particularly vulnerable to low light levels at night[2]. Although the Moon is visible for most of the month, it dominates the sky all night only near full Moon (Figure 1). During most of the crescent phases, it is much fainter, and sets soon after sunset, or rises only just before dawn.

Although the Moon is the dominant light source at night, its limited duration allows some animals to temporarily modify their behaviour, perhaps by restricting the extent of their foraging[3], then recover during the following three weeks of "dark time."

The biochemistry and behaviour of all life has evolved to tolerate and even depend on these photo cycles as cues to seasonal change[4]. We experience random temperature variations over a few days or weeks, so temperature alone is not a good cue for seasonal change. The cycle of light and dark is the one constant characteristic of the Earth's environment—even as the rest of the environment has changed and evolved: air composition, distribution of landmasses, and predator-prey relationships.

Short-term variations have caused species to adapt, while longer-term variations have forced them to evolve. The result of evolution is a new step on the evolutionary ladder. Missteps and broken rungs are revealed as impressions in rock lamina and fossils in the Palaeolithic record. Change in the environment has been marked by extinctions and new species that form new and higher rungs.

Dusk and Dawn

Although we use the rising Sun to mark the beginning of our day, the most influential marker is nightfall[5]. The biochemistry in plants and the detection of threshold illumination in our eyes are two cues to nightfall as it resets circadian rhythms to compensate for slow diurnal drift and seasonal variations. Masking these cues with artificial light makes animals, and some plants, ill prepared for the seasonal changes—especially in the temperate latitudes of North America and Europe that have the highest density of ALAN.

The greatest change in the illumination level occurs at dusk and dawn, and this is used to synchronize, or entrain, biological rhythms to the light-dark cycle. These transition times are most effective at entrainment because the effect of cloud cover produces only a few minutes of error[8]. For some plants, entrainment ranges from very weak at about 0.6 Lux (about twice the brightness of the full Moon) to being "saturated" at 10 Lux (about 20 minutes after sunset, Figure 2). This is in the range of bright urban artificial light. It is not surprising

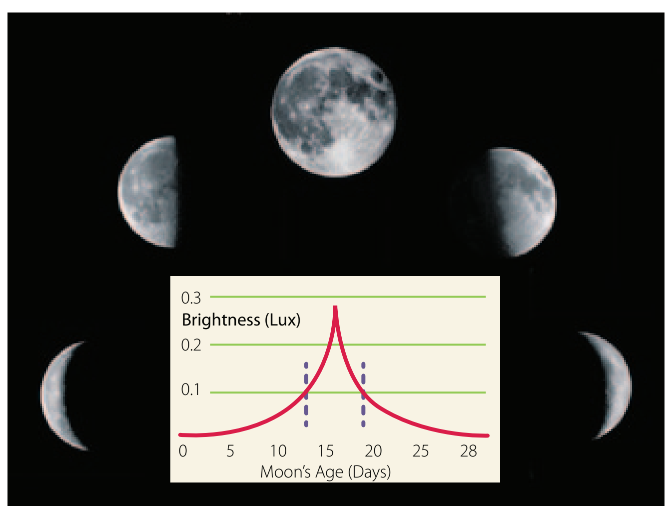


Figure 1 — Brightness of moonlight over a cycle of one phase [6]

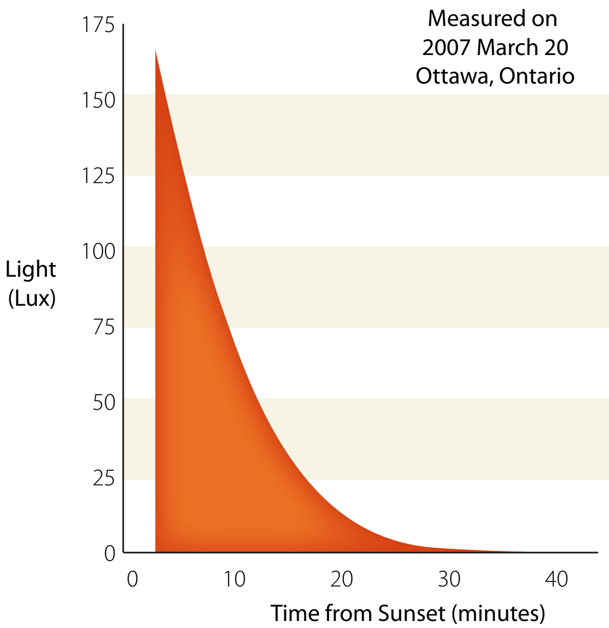


Figure 2 — Measurements of sky brightness during dusk

that many plants cannot survive in the urban environment as shown by casually comparing urban and rural flora.

During twilight, there is also a shift in the colour of the sky. During the day, the Sun with its dominant green-yellow spectrum, illuminates the landscape (Figure 3). Just after sunset, illumination is primarily from red light and blue scattered light in the atmosphere, particularly around a wavelength of 480 nm. As the sky darkens below the visual threshold of most life forms, the absence of blue signifies night; conversely, the increase of scattered blue light in the morning marks the end of night.

Humans have historically been active during twilight—helped by the combination of both photopic and scotopic vision (cone and rod cells, respectively), which is collectively called our mesopic vision. However in the afternoon, our circadian rhythm has already begun to prepare our restoritive hormones for nightfall and the decrease in blue light causes non-visual ipRGC cells in our eyes to prepare us for sleep. Unfortunately, the blue light in ALAN can overwhelm these cues and prevent or delay the release of the restorative hormones, and reduces the effectiveness of our rest.

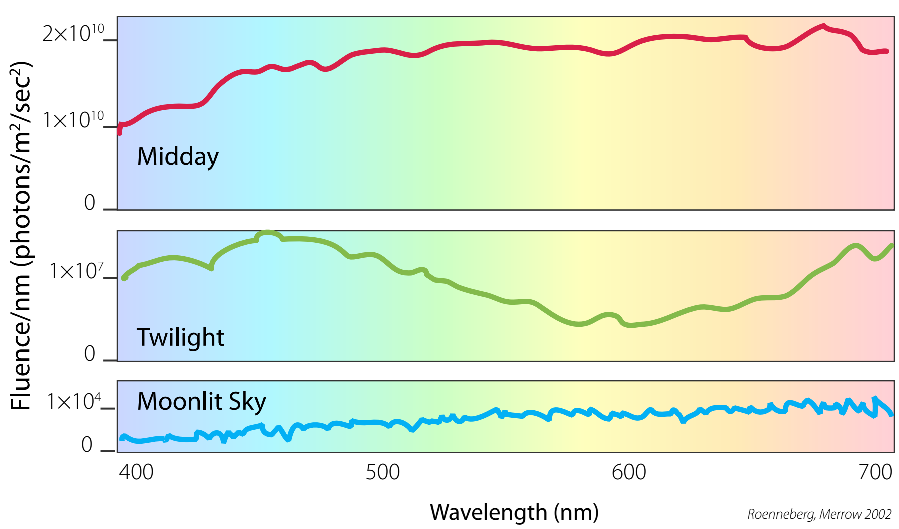
Evolution and Adaptation

There are three aspects to evolution: physiology, biochemistry, and behaviour, and they act over very different time scales. The physical evolution works on scales of millions of years as suggested in the Palaeolithic record.

Biochemistry refers to the chemical mechanisms that animate life. After the surface of the Earth solidified over 4 billion years ago, it took several hundred million years before the chemistry in the first rudimentary cells was established. Since there is no preserved record of the earliest biochemistry, it must be inferred from our knowledge of the earliest terrestrial environment and laboratory experiments. It is reasonable to assume that biochemical change is also very slow.

We choose to define behavioural change as non-physical change occurring within an individual's lifetime. New, learned behaviour modifies the *status quo*[9] but behavioural adaptation and developmental plasticity[10] needs a few generations to be fully integrated into a species' way of life. Species have both innate subconscious behaviour and conscious learned behaviour and altering their natural environment can lead to their miss-application and inappropriate behaviours.[11]. Although learned behaviour can change quickly, extensive behavioural change and the subsequent "trauma" to the

Figure 3 — Sky spectra for daytime, dusk, and nighttime under moonlight[7]. Moonlight spectrum is similar to that of our Sun, which also approximates that of starlight. It is representative of the overall night sky, except brighter by about a factor of 100[11].



ecosystem may require several species-lifetimes to stabilize, as the ecological balance is re-established.

More wildlife is active after dark than during the day[12]. One could then argue that darkness is more critical to life on Earth than light! Many foraging species eat primarily plants, scavenge, and take advantage of the anonymity of darkness to avoid predation. They also seem to interpret the longer nights as a cue for winter[13].

An example of a non-obvious daily dependence is zooplankton in marine and inland waters[14]. Darkness governs the time and depth of their vertical migration. During the day, they remain in the depths where they enjoy relative safety afforded by darkness. They rise to the surface at night where they feed on plant life. Even moonlight can provide sufficient illumination to raise their vulnerability to predators, so some zooplankton limit the range of vertical migration during full Moon as an unconscious behaviour to avoid predation[15]. Adding opaque dyes to water reduces aquatic plant growth[16], so near urban areas, sky glow can be bright enough to encourage plant growth. It can also modify the behaviour of zooplankton—together perhaps contributing to algae blooms near illuminated shorelines where sufficient nutrients are available.

Although nocturnal species are comfortable at night, they still need to navigate across their foraging grounds. Insects use distant lights to determine direction[17]. Birds use the northern stars for orientation during migration resorting to secondary cues only when it is cloudy[18]. Artificial lights are misinterpreted as stars or can alter the appearance of the ground navigation markers, which confuses wildlife. Precious foraging time is lost as they try to find their way, and this delay may be lethal if they are caught in the open by predators. So, although sky glow from urban lighting is a problem, isolated rural lights that are not shielded also impact wildlife.

Benefits of Darkness

Even with our relatively safe urban life styles, our bodies require periods of "down time" to repair damage, fight infection and disease, and to purge and store our daily memories, etc. We share at least some of these restorative processes with wildlife. Biology has evolved over millions of years to take advantage of nighttime to sleep. These biochemical processes cannot change as quickly as the growth of ALAN.

Even in our fast-paced life style, most people go to bed once it is dark. This affords them the maximum duration of rejuvenation. However, our technology, and the life styles that have developed out of its application, complicates this process. Those who use white night lights, watch television and computer monitors late at night, or have exterior light that shines into their bedrooms, are short-changed of this natural health benefit. The blue spectral components in this light convince our bodies that it is still daytime, and delay the release of hormones that produce the restorative benefit of rest. Illumination levels of the full Moon and brighter will disrupt the release of our sleep-inducing hormone melatonin[19].

Summary

There is evidence of natural ecological experiments extending over billions of years. Failures are recorded as both limited and extensive extinction events that delineate the transitions in the Palaeolithic eras. The present delicate ecological balance is the current rung on the evolutionary ladder. Any change to the environment, whether natural or human engineered, will push the world up to the next step. We now believe human-induced change to the environment will play a significant role in the making of this next rung.

Since the ecosystem is a balance of all life, altering the viability of the most basic creatures can change the entire system with yet-unknown consequences. Although complex organisms may tolerate the initial environmental change, the more basic organisms, on which the ecosystem depends, may not. Over the last few decades, we have refined our activities to counteract some of our earlier unexpected ecological experiments (air and water pollution, creation of micro-climates, *etc.*), but the remediation has been expensive and only partially effective. A degree of change persists after all our attempts to re-balance the ecosystem. Therefore, in order to maintain the *status quo*, it is better to not alter the environment in the first place.

ALAN is one such assault on the natural environment. The complexity of the current ecosystem prevents us from predicting the consequences, but all previous human interventions have resulted in unforeseen change—all of which impact human expectations for a good and healthy life. Compared to natural environmental change, our experiments in the use of extensive ALAN has been brief and limited primarily to large urban areas. ALAN is altering the environment in urban areas, but the resulting sky glow impacts a region out to about 100 km radius—a distance at which the level of sky glow is comparable to the full Moon.

Concern about the effects of artificial light is not universal. A major lighting industry report[20] could not find sufficient evidence against ALAN. Much of the concern focused on direct physical damage. However, scotobiology highlights the subtle, yet profound changes wrought by ALAN. *The Scientific Committee on Emerging and Newly Identified Health Risks*[20] states there is only a low probability that artificial light will induce acute pathological conditions since the illumination levels are typically lower than natural daytime

illumination. The much lower level nocturnal exposure was not given equal weight.

They did admit, however, that ALAN might aggravate the symptoms of pathological conditions. Their chapter on the impact of ALAN, referred to as ill-timed lighting, acknowledged the lack of extensive research into the effects of nocturnal lighting on human health, and agreed that citizens should be better informed of the health effects of ALAN.

Scotobiology shows that ALAN, when used with restraint, need not significantly impact the ecosystem. It is not only inexpensive to alter this human behaviour; it will also offer the co-lateral benefits of reduced energy use, scaled down power distribution systems, and improved health and well-being.

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Light and Dark and Human Health

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Humans evolved under both a light and dark night cycle. Therefore, it is not surprising that modifying natural, cyclical daylight and dark exposure would lead to severe health risks. It must be emphasized that the dark periods are equally important as the light period for proper human health and well-being.

Cyclic daylight and dark night exposure controls the fluctuation of the body's production of various hormones; this is known as the circadian rhythm with about a 24-hour period. The human circadian system is regulated by both environmental stimuli and endogenous (internal) clocks. Visible light between 460 – 500 nm (Gaddy *et al.*, 1993) received by the human eye is one of the regulators of the circadian response in humans (Figure 1). The photosensitive molecule (chromophore) that receives this circadian light is melanopsin, which is located in the neural retina in the intrinsic photosensitive Retinal Ganglion Cells (ipRGC)

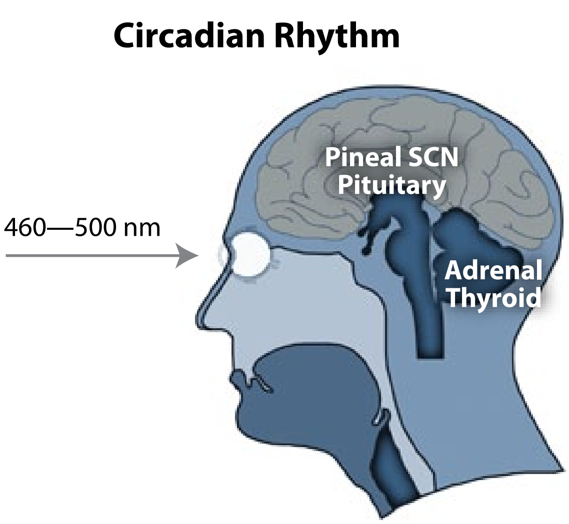

Figure 1 — The most powerful external regulator of the circadian response in humans is visible light, which is transmitted through the eye. When visible light impinges on the retina (intrinsically photosensitive Retinal Ganglion Cells), it sends a signal to the suprachiasmatic nucleus (SCN) in the hypothalamus leading to a cascade of hormonal changes in the pituitary, pineal, adrenal, and thyroid glands.

Table 1

Circadian Blue Light 460 – 500 nm, Morning 6 – 10 am

Neurotransmitters	
Cortisol	stress response
Serotonin	impulse control, carbohydrate craving
Dopamine	pleasure, alertness, muscle coordination
Neurohormones	
CRF	stress
Gastrin Releasing Peptide	hunger
Neuropeptide Y	hunger
FSH	reproduction
TSH	metabolism

(Berson 2003). When circadian light impinges on the retina, it sends a signal to the suprachiasmatic nucleus (SCN) (Brainard *et al.*, 2001) in the hypothalamus and from the hypothalamus, to the pituitary, pineal, adrenal, and thyroid glands to produce a specific set of hormones. Circadian blue-light exposure in the morning (Table 1) increases the hormones: cortisol [for stress], serotonin [for impulse control], gamma amino butyric acid (GABA) [for calm] and dopamine [for alertness] levels, and it modifies the synthesis of follicle-stimulating hormone (FSH) [for reproduction], gastrin-releasing peptide (GRP), neuropeptide Y (NPY) [for hunger], and thyroid-stimulating hormone (TSH) [for metabolism] (Brewerton *et al.*, 1995; Roberts, 1995; Wehr *et al.*, 2001; Cardinali and Esquifino, 2005; Veitch *et al.*, 2004; Praschak-Rieder *et al.*, 2008; Sookoian, 2007; Van Someren and Riemersma-vander Leka, 2007; Werken *et al.*, 2010).

The morning production of the hormones serotonin, dopamine, and GABA are essential for mental health. Insufficient serotonin and dopamine results in sadness, decreased energy and libido, increased need for sleep, and strong cravings for carbohydrates, while the deprivation of sufficient GABA leads to anxiety. Unusual food cravings are a result of the circadian imbalance in the hunger hormone GRP and NPY and thyroid TSH imbalance. These symptoms are a result of a lack of circadian blue light or daylight in the morning. They are most common in the winter [Seasonal Affective Disorder (SAD)] (Glickman *et al.*, 2006) or when crossing several time zones [Jet Lag] (Cho, 2001; Eastman *et al.*, 2005) and Shift Work Dysfunction (Arendt 2010)

Some hormones are made only in the dark (or red light) (Table 2), for instance melatonin [for sleep], vasointestinal peptide (VIP) [that lowers blood pressure], and growth hormone (GH) [for metabolism and repair]. Staying up at night and sleeping during the day will disturb this nighttime dark hormonal production. The "dark" hormones, melatonin, VIP, and GH are primarily produced during deep delta "restorative" sleep. The state of sleep has two components: REM (rapid

Table 2

Circadian Dark Response – above 600 nm
No circadian blue after 10 pm

Neurotransmitters	
Melatonin	sleep
Vasoactive Intestinal Peptide	blood pressure
Growth Hormone	decreased body fat

eye movement) and SW (slow-wave sleep). With REM sleep, the brain, eye, and body muscles are active and we dream; slow-wave sleep is when the brain's activity is slowed down. Slow-wave sleep is further classified as delta (deep sleep) or theta (light, drowsiness). (Table 3) During deep-delta "restorative" sleep, stress-related hormones and blood pressure decreases while the anti-aging growth hormone increases. Imbalance in these dark hormones leads to high blood pressure, and abnormal weight gain (Spiegel *et al.*, 2005; DiLorenzo, 2003; Arendt, 2010).

Delta (restorative sleep) cannot be attained without the presence of the sleep hormone melatonin. Under normal nighttime darkness, melatonin is produced between 10 p.m. and 4 a.m. As the dawn (6 a.m. – 10 a.m.) brings exposure to blue circadian light, melatonin is converted to serotonin. Melatonin production is blocked if there is ocular exposure to visible light at night instead of darkness. The slightest blue or white visible light (2 lux blue light or 24 lux white light that is emitted from the flicker of the bathroom light, a night-light, computer screen, TV, or cell phones, is sufficient to disrupt the production of melatonin and therefore interfere with deep restorative sleep (Gooley *et al.*, 2010). Even with proper darkness, only 15% of a good night's sleep is delta sleep and this percentage naturally decreases with age. Furthermore, a nap during the day will only reach about 5% total delta sleep.

Insufficient circadian blue light in the morning and/or visible light in the evening will result in mood swings, confusion, irritability, depression (AMA 2012; Stevens *et al.*, 2007) due to the lack of or decreased production of important neurotransmitters and neurohormones. [Table 1 and 2]
It is not only mood that is disturbed by circadian rhythm disruption but overall health. There is an increased risk for

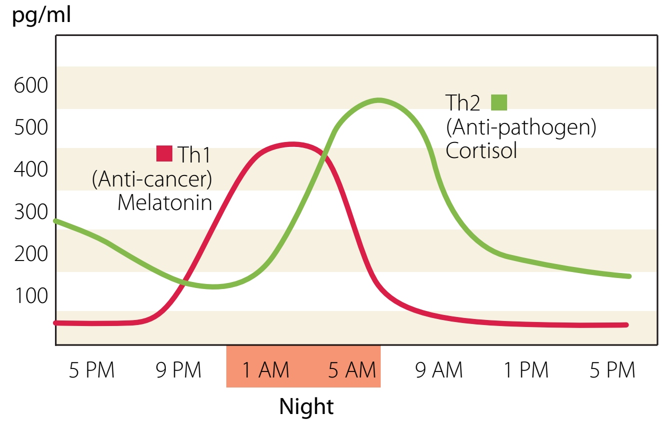

Figure 2 — The human immune response is circadian. Th1— involves cytotoxic T-Cells and N-Killer cells. These anti-tumor cells are activated in the evening (in the dark, in the absence of circadian blue light) by the presence of melatonin. Th2—involves B Cells. These anti-pathogen cells are activated in the morning in response to circadian blue light (480 nm) by the presence of cortisol and other neurotransmitters. (Adapted from Cutolo, M., Maestroni, G.J. et al.,*" 2005)*

cancer and infectious disease if one is exposed to insufficient daylight in the morning or darkness in the evening. How is this possible? This is because the human immune system is circadian.

The human immune response consists of two major pathways: Th1 (T helper 1) [cell-mediated immunity], which uses N-Killer (NK) cells and cytotoxic T cells to destroy viruses and cancer, and Th2 (T helper 2) [humoral or antibody-mediated immunity], which enlists B cells to produce specific antibodies to help eradicate bacteria, parasites, and toxins (Figure 2). The Th1 immune response is most active in the evening, at least partly in response to the nocturnal production of melatonin, while the Th2 immune response is activated in the morning, in response to the production of cortisol and other morning neurotransmitters. An imbalance of Th1/Th2 immune responses can trigger an autoimmune response. Autoimmune diseases (asthma, rheumatoid arthritis) are more prevalent in the morning, while light at night prevents the nocturnal melatonin production, preventing the activation of the anti-cancer N-Killer (NK) cells and cytotoxic T cells. Night workers have a particular risk for breast and prostate cancer because of the disrupted production of melatonin. Exposure to

Table 3

Alertness and sleepiness may be quantitatively measured by noting the changes in the electroencephalographic (EEG) power spectrum. In general, the lower the number (Hz) the slower the brain pattern.

Slow Wave Sleep			**12 – 14 REM Sleep**	
Delta	**Theta**	**Alpha**	**Sigma**	**Beta**
0.5 – 4 Hz	4 – 7 Hz	8 – 13 Hz	11 – 15 Hz	13 – 40 Hz
deep	Light	alert	focused	vigilant

visible light at night also deregulates the circadian gene, Per2 (Chen *et al.*, 2005; Fu *et al.*, 2002), which is involved in human breast and endometrial cancer development. For this reason, when the natural circadian immune cycle is disrupted, there is an increase risk of cancer, autoimmune, and infectious diseases (Roberts, 2000, 2008; Cutolo *et al.*, 2005; Baldwin and Barrett, 1998; Levi, 2000; Blask *et al.*, 2005; Blask, 2009; Dimitrov *et al.*, 2004; Erren and Reiter, 2008; Spiegel *et al.*, 2005; Hu *et al.*, 2011; Maestroni, 2003).

There have been numerous clinical trials studying the affect of appropriate and inappropriate lighting on circadian dysfunction and human health. They involve varying lighting regimens, including enhanced circadian blue light in the morning to increase alertness and red light at night to enhance sleep. For shift workers, blue-blocking glasses in the morning were used to prevent circadian stimulation, and enhanced daytime darkness and/or melatonin to aid in restorative deep (delta) sleep. Dark/light control of the human circadian response has been directly applied to treating sleep disorders and other circadian disorders (Arendt *et al.*, 2008; Arendt 2010; Gooley *et al.*, 2012; Burkhart & Phelps 2009; Glickman *et al.*, 2006; Kent *et al.*, 2009; Lockley *et al.*, 2003; Lieverse *et al.*, 2008; Levi & Schibler 2007; Scheer *et al.*, 2009; Werken *et al.*, 2010; Pechacek *et al.*, 2008). Modifying diet at specific times of day has also been found to help overcome jet lag and rebalance shift work circadian disruption (Wurtman *et al.*, 2003; Mendoza, 2007). For instance, eating tyrosine- (the precursor for dopamine) containing foods increases alertness, and eating tryptophan- (precursor of serotonin and melatonin) containing foods enhances serenity and sleep.

These studies are only valid if precise measurements have been made that involve age of recipient, the definition, spectrum, intensity, the time of day of exposure, and direction of the light source (Portaluppi *et al.*, 2008; Van Someren, 2011). It is particularly important that the report includes a detailed description of the spectral properties of the light source and the total irradiance at the action spectra of non-visual photoreception (460-500 nm). Terms such as "Bright Light" and "Dim Light" or continuous light (LL) and continuous dark (DD) are biologically irrelevant and not reproducible.

In summary, exposure to the appropriate spectrum of light during the day and evening enhances human health and well-being, immune response, and productivity (Figure 3). Because of these hormonal changes, the circadian dark/light cycle controls and modifies the sleep/wake cycle, blood pressure, metabolism, reproduction, and the immune response. Removal of circadian blue light exposure at night allows for an appropriate circadian response. However, exposure to light sources that do not match the natural solar spectrum to the time of day or evening is hazardous to human mental and physical health.

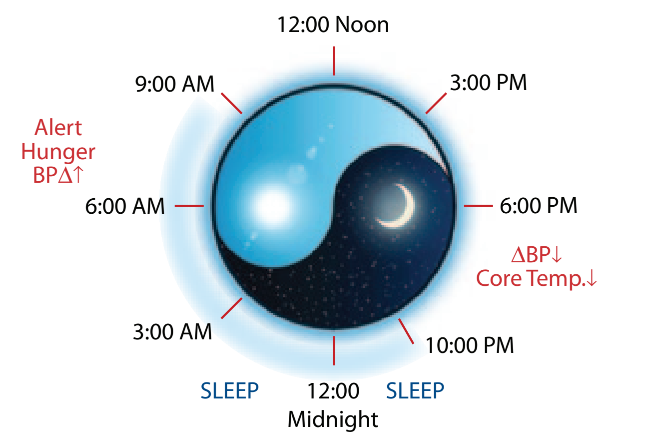

Figure 3 — The circadian dark/light cycle controls hormonal change, which modifies the sleep/wake cycle, blood pressure, sleep, and other physiological functions.

Acknowledgements

Special thanks for the graphics designed and created by David Green, NIEHS Multi-Media Services, North Carolina.

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Lighting in the Roadway Environment: Aims, Advances, and Alternatives

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According to the *American National Standard Practice for Roadway Lighting* (IES 2000), the primary recommended practice for road illumination in Canada and the United States, roadway lighting is installed with the following objectives:

- To reduce nighttime crashes
- To efficiently control traffic flow
- To help reduce crime
- To promote economic development

Evidence that roadway lighting meets these objectives varies in quantity and quality, and is strongest for crashes (CIE 1992; Donnell *et al.*, 2009). Benefits of lighting appear to come primarily through increased visibility (Rea *et al.*, 2010), but it is less clear whether or how lighting improves traffic flow (Huber *et al.*, 1968). Evidence linking roadway lighting to reduced crime (Tien *et al.*, 1979) and to economic activity such as in urban downtowns is ambiguous.

The IES (2000) presently includes three design metrics for roadway lighting: illuminance (the amount of light incident on the road surface, in lux), luminance (related to the apparent brightness of pavement toward drivers' eyes, in candela/m^2), and small target visibility (STV, an analytical procedure related to the visibility of 20-cm square light-gray targets along the road). STV is rarely if ever used, and future revisions of this document will probably only include the luminance method because it is thought that luminance is more closely related to what the driver perceives. In general, higher levels are specified for roads with greater traffic and pedestrian use. For example, a local road with few pedestrians requires an average luminance of 0.3 cd/m^2, while a major road with many pedestrians requires an average of 1.2 cd/m^2.

The levels recommended by IES (2000) are provided by pole-mounted luminaires, often containing high-pressure sodium (HPS) lamps. HPS lamps produce yellowish illumination, are very efficient, have relatively long life, and maintain their light output for most of that life (lumen maintenance). These attributes make them attractive to roadway engineers. A growing proportion of white-light sources, including metal halide, fluorescent induction, and light-emitting diodes (LEDs) are also in use (Radetsky 2010).

Near astronomical observatories, low-pressure sodium (LPS) lamps are sometimes used; these produce nearly monochromatic yellow light. Despite the lack of color perception under LPS, it is easy to filter by astronomers and has very high efficacy, among other benefits (Rea and Bullough 2004).

The whiter light sources have captured much recent attention with respect to roadway lighting. Among the reasons for this is a growing body of research (IES 2006) and recommendations (CIE 2010; IES 2011) suggesting that visual performance under illumination with a larger proportion of short-wavelength energy is improved, relative to one with more longer-wavelength energy like HPS or LPS, even for the same measured light level. The human eye contains two primary visual receptor types, cones and rods. Cones support vision at levels corresponding to daytime and interior lighting conditions. Rods exclusively support vision at very low levels, when no electric lighting or even moonlight is present.

For a range of light levels corresponding to some used in roadway lighting, a combination of cones and rods underlies vision. This would merely be of academic interest but for the fact that the peak spectral sensitivity of rods corresponds to shorter wavelengths than the combined peak sensitivity of cones. Spectral sensitivity for visual performance shifts toward shorter wavelengths as the overall light level is reduced. For commerce and specification, the definition of light is based solely on cone sensitivity—the *photopic* luminous efficiency function shown in Figure 1. This figure also shows the spectral sensitivity of rods—the *scotopic* luminous efficiency function, as well as one particular intermediate function representing combined cone and rod sensitivity, a *mesopic* luminous efficiency function, which is an additive weighting of the photopic and scotopic functions. Even in the presence of glare from roadway or automotive lighting, visibility in other

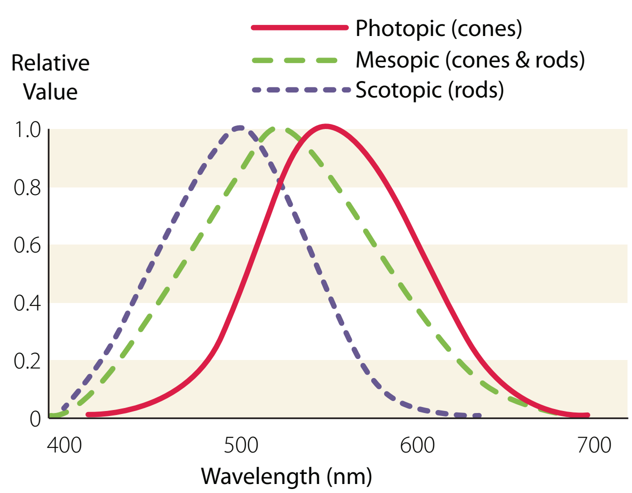

Figure 1 —Normalized photopic (cones), scotopic (rods), and mesopic (cones and rods) spectral sensitivity functions.

parts of the field of view exhibits a mesopic spectral sensitivity (Akashi and Rea 2002), suggesting that mesopic adaptation is largely local across the eye's visual receptors.

The practical implication of Figure 1 is that, at many nighttime lighting levels, the visual system has greater sensitivity to shorter-wavelength light than implied by the photopic function, and if two light sources are used to provide the same (photopic) light level, visual performance can actually be improved under the one with a higher proportion of short-wavelength energy. Laboratory, field experiments, and real-world demonstrations suggest that for some types of roads, using whiter sources than HPS could permit (photopic) light-level reductions of 20% – 40%, while maintaining visual performance and acceptability (Akashi *et al.*, 2007; Fotios and Cheal 2007; Morante 2008).

Light sources with greater short-wavelength content might have some drawbacks, however. Perceptions of discomfort glare are greater from sources with more short-wavelength energy (Bullough 2009). Also, short-wavelength light produces somewhat more sky glow than longer wavelengths, but the differences between HPS and bluish-white LED spectra are typically 10%-20% for equal (photopic) light levels (Bierman in press), and might be overcome by taking advantage of reduced levels to account for the spectral sensitivity shift for visibility deduced from Figure 1.

Of course, spectral differences between HPS and other light sources, particularly LEDs, are not the only differences with practical significance for roadway lighting. Although HPS is dimmable and has been for many years (Ji and Wolsey 1994), the relative ease with which LEDs, being direct-current sources, can be dimmed via input current control or pulse-width modulation has increased interest in adaptive roadway lighting (Bullough 2010). When traffic volumes are low, such as after midnight (Ivan *et al.*, 2002), light-level reductions will reduce visibility but affect fewer drivers. At the same time, this strategy in combination with higher-than-usual levels during peak traffic, could result in no net change in roadway lighting energy use, but a net increase in the benefit/cost ratio of roadway lighting (Bullough and Rea 2011). This is because lighting costs are independent of traffic volume, but the benefits are directly correlated with traffic volume. Further, roadway lighting can be superfluous in locations where commercial lighting is present (Rea *et al.*, 2010), and ambient light sensors could be used to adjust roadway lighting when such illumination is available. Using lighting only when and where it is beneficial will be an increasingly critical consideration in present times of municipal budget tightening.

Not yet discussed is the spatial distribution of light from roadway luminaires. Obviously, fully-shielded luminaires that emit light only downward are beneficial to reducing light pollution (Zhang 2006), and the IES (2007) has developed a system to classify roadway luminaires based on the amount of output they produce in various angular regions around the luminaire, such as the backlight, upward light, and glare (BUG) regions (IES 2007). Using this system can help minimize sky glow from upward-emitted light and light trespass that can impact adjacent properties. Luminaire classification alone, however, is not the only important consideration for limiting light pollution. Waldram (1972) estimated that most sky glow from roadway lighting was caused by light reflected from the roadway and adjacent surfaces, which is not necessarily reduced by limiting upward illumination. Such findings reinforce the potential benefits of temporal control of roadway lighting.

Finally, when discussing roadway lighting it is necessary to consider that roadway lighting is only one part of the *roadway visibility system*, which also includes retroreflective signs and markers, traffic signals, and vehicle lighting. In North America, most roads and highways are not illuminated by pole-based roadway lighting systems. Vehicle headlights have a substantial role to play in nighttime driving safety. It is worth noting that LEDs, because of their ease of controllability, will be important in the development of adaptive forward-lighting systems (AFS) that adjust headlamp intensities and distributions based on road geometry, weather, and traffic presence. Drivers consistently under-utilize their high-beam headlamps (Sullivan *et al.*, 2004), in part to avoid producing glare toward other drivers. Adaptive high-beam systems that can reduce intensity (and therefore, glare) toward oncoming drivers will have practical benefits (Skinner and Bullough 2009) and are beginning to be practical with LED control (Sanchez and Reiss 2011). To the extent that headlamp system advances can make roadway lighting less necessary, they might also facilitate reduced light pollution from roadway lighting systems, and less interference with astronomical observation.

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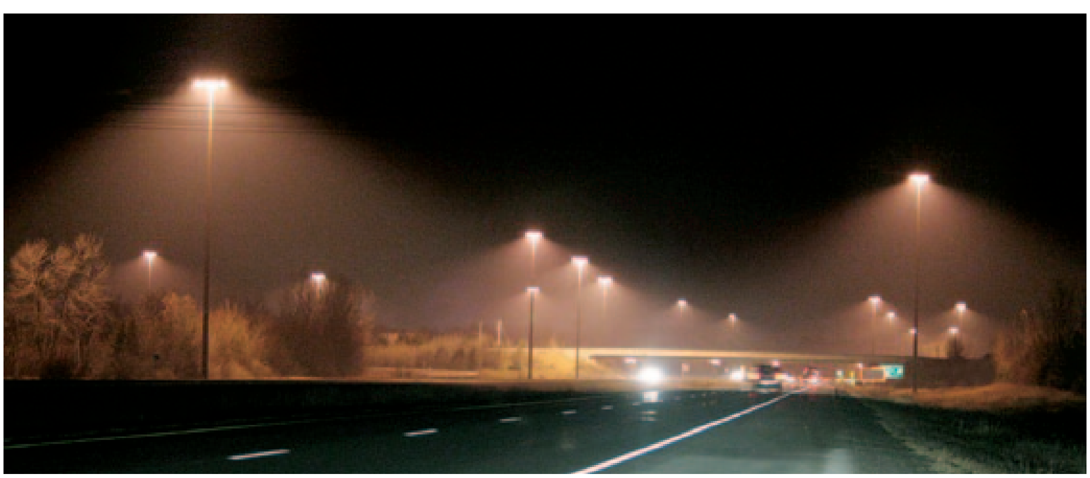

Roadway lighting highlights an area where heightened attention is needed, such as in this interchange with Hwy 416 and Hunt Club Road in western Ottawa. These full-cut-off luminaires improve visibility while limiting the impact on the surrounding forest and open fields. (Nov. 2011, R. Dick)

LEDs in Outdoor Lighting

– Robert Dick

Abstract

For almost 150 years, incandescent bulbs have persisted as a symbol of our modern electrified world. The continued development of solid-state lighting is causing a revolution in lighting. Light-emitting diodes (LEDs) are being promoted as lower-power light sources that rival the light output of the older technologies. Although commercially available LEDs are not much better than modern high-intensity discharge (HID) bulbs such as high- and low-pressure sodium (HPS and LPS, respectively) and metal halide (MH), near-term developments are expected to push them into the lead.

However, LEDs are so different from the older light bulbs that they require a change in the way light fixtures are designed and used. If the transition to a new lighting philosophy is successful, the adoption of LED lighting can help reduce light pollution.

Background

Solid-state lighting (SSL) is based on semiconductor technologies and manufacturing methods. As a new technology, the introduction of LEDs is creating problems[1]: low-quality LED products, high initial purchase cost and rapid obsolescence, biological safety of the light, and users unaware of LED capabilities and weaknesses. In this article, we will discuss a few of the LED capabilities and weaknesses. We will first compare incandescent, HID, and SSL technologies.

Technology

Incandescent bulbs use the electrical resistance of tungsten wire to create light. The resistance to current flow raises the temperature of a tungsten filament to several thousand degrees—a temperature limited by the melting temperature of the filament material. The surface of the filament emits light as thermal radiation, which has a spectrum that depends on the temperature. The distribution of light follows the Planck radiation "black body" curve that has a peak in emission at a wavelength of 2898/T, where the wavelength is given in microns (millionths of a metre) and temperature (T) in Kelvins.

The maximum filament temperature is about 3500K, so its spectrum peaks in the infrared (about 0.83 microns). Since our eyes cannot see beyond about 0.7 microns, most of the light emitted by an incandescent bulb is emitted as heat, not visible light. This inefficiency in producing light has resulted in plans to phase out the use of incandescent bulbs as an energy conservation measure. The rationale for this policy is still being debated by those aware of the physics of lighting[2].

HID bulbs use a different process. Electrodes excite a gas in a sealed ampoule. This gas emits light at the characteristic wavelengths of the fill gas. Adding other gases changes the emitted spectrum—giving the light different colours, from yellow with HPS bulbs to white, using more complex mixtures, in MH bulbs.

A modification of the HID bulb is a fluorescent bulb that has a phosphor coating on the inside surface of the ampoule to further spread out and tailor the emitted spectrum and give a more refined emitted colour.

These three types of light bulbs are based on heating the emitter to very high temperatures, so that considerable effort must be made to maintain a reliable seal between the hot metal electrodes and cool glass ampoule. This makes the bulbs susceptible to breakage if mis-handled.

LEDs operate on a completely different principle that frees them from the limits of high-temperature filaments, discrete emission lines in the spectrum (Figure 1), and delicate glass ampoules.

Light-Emitting Diodes

LEDs operate at the atomic level between two dissimilar regions in a semiconductor chip. The base material is infused with a very small number of other atoms in a process called doping. That produces two regions—one with an excess of

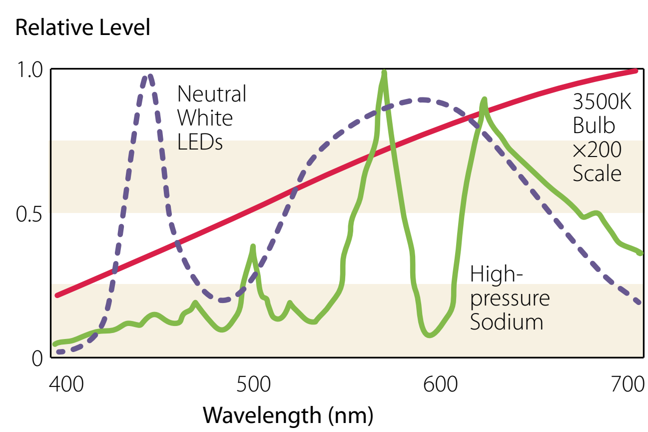

Figure 1 — The spectra of most artificial light sources consist of emission lines, or bands that are significantly different from the black-body emission of thermal sources (the Sun and incandescent bulbs). Therefore, defining their spectrum by their colour temperature is not appropriate.

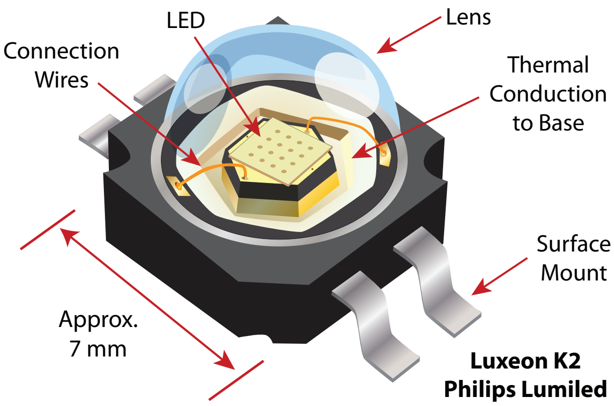

Figure 2 — The LED chip is only a very small part of the LED module, which itself may be only a few millimetres across (Philips Luxeon K2 LED product).

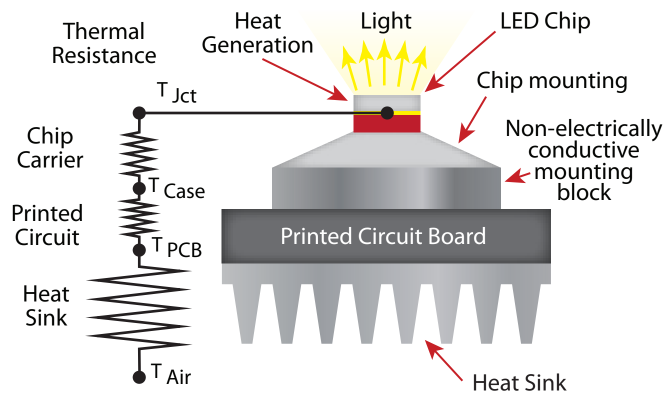

Figure 3 — Thermal conduction from the diode junction in the LED chip passes through a number of resistive interfaces. Ultimately, the heat is dissipated to the air.

free electrons, and the other with a shortage of free electrons called holes. An applied external voltage forces the electrons into the holes, reducing their energy. The leftover energy is emitted as light, and the colour of the light is engineered by doping the material such that the energy difference corresponds to the desired wavelength. As long as the external voltage is applied, the process can continue more or less indefinitely. Only after a service life of typically 10 to 50 years do wear mechanisms inside the semiconductor accumulate to the point where the LED will cease to operate.

The semiconductor dies are on the order of less than a millimetre across, making them difficult to handle (Figure 2). This also limits the amount of light each chip can produce, so, for practical reasons, several chips are usually mounted in clusters on a chip carrier.

The infusion of the doping atoms is enhanced by heat, so at high temperatures, the atoms that were added will migrate away from the junction. This mechanism, and the potential failure of the other materials and bonds in the LED assembly, will cause the device to fail. Therefore, LEDs, as with all semiconductors, must be kept cool. The best reliable operation is at room temperature.

Thermal Issues with LEDs

A voltage is needed to maintain the current through the die. This current, times the voltage to maintain the current, results in power dissipation in the chip. Typical LEDs require between 2 and 3.5 volts and operate at currents between 0.1 to .8 amperes. As much as about 3 watts of heat are dissipated in each LED and must be removed or it will fail.

Although 3 watts does not seem like very much power, the removal of this amount of heat is a challenge for the designer of the LED module. Unlike the "light bulb" concept with a glass surface area of about 100 cm^2, the small size of the LED, a few millimetres on a side, cannot rely on natural convection to remove this heat. The cooling of the chip is solely dependent on the emission of light energy and thermal conduction to a much larger surface. From there, natural, or even forced, convection can keep the device cool (Figure 3).

The thermal pathway has several interfaces. There is a thermal resistance to the LED case of typically 6 – 10 °C/w. The printed circuit board can have a resistance of perhaps 20 °C/w, and the heatsink-to-air interface can be perhaps another 20 – 30 °C/w. A simplistic thermal design will cause rapid failure of the LED by overheating.

There are a number of failure modes for semiconductors, from the diffusion of atoms in the semiconductor to manufacturing issues. However, in general, raising the temperature of the LED by 40 °C above room temperature reduces the life by a factor of ten[3]! Heat is a critical issue when using LEDs as a light source.

A second thermal problem with LEDs is the energy in the light. In the case of the incandescent and florescent bulbs, the heat generated in the lamp is much greater than the light energy. However, for LEDs, the light itself can heat the surrounding optics to cause failures. Placing your finger too close to a high-powered LED can cause a burn.

Colour of LEDs

Unlike HID bulbs, which produce an emission-line spectra, and incandescent bulbs, which emit light across a wide range of wavelengths, an LED spectrum is a narrow band, about 0.1 microns wide. We find these LEDs in red flashlights and indicator lamps. The relatively narrow spectrum that is produced, compared to our Sun, which is the reference when judging colour recognition, provides very poor colour rendering. Any surface that is not red will appear dull brown or black under the illumination of a red LED.

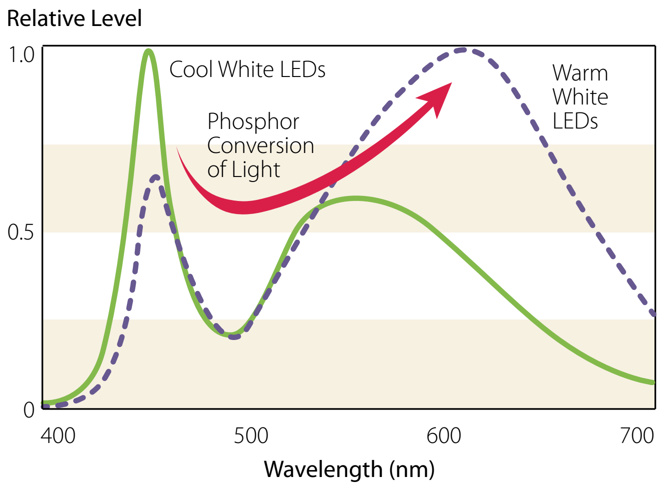

Figure 4 — In phosphor-converted LEDs, the phosphor is excited by a blue LED; the energy is re-emitted at longer wavelengths. As more blue light is converted, the light looks less blue-white and more warm-white.

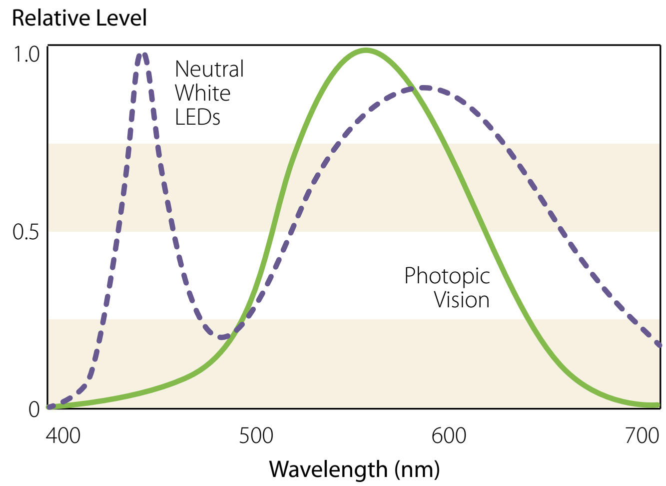

Figure 5 — The blue peak of a white LED falls well out of the sensitive bandwidth of our photopic vision. As a result, a strong blue emission is needed for us to see white.

LED manufacturers have solved this problem by adding a phosphor coating to the surface of the LED (Figure 4). The phosphor absorbs the light from the LED and re-emits it with a broader spectrum, which is defined by the selection of the phosphor.

In order to excite the phosphor, an LED with a shorter wavelength and higher spectral-energy light is needed. As a result, such "phosphor converted" LEDs are based on a blue LED exciter. If a thin layer of phosphor is used in such devices, then a significant amount of blue light will escape. When combined with a phosphor to produce a longer-wavelength spectrum, the result is white light. Less escaping blue light will produce "warm white." If no blue light escapes, the colour is "amber" with a spectrum between 500 nm and over 650 nm.

The duo-peak structure of the white LED emission is very different from other light sources. Consequently, the existing metric used to define the colour quality of the light is not applicable (Figure 5). The basis for this problem is that our perception of colour has evolved to depend on a continuum light source like that of our Sun (with a colour-rendering index, CRI=100). Except for incandescent lights, no artificial light sources have the correct shape of the Sun's radiation curve (Planck function). The industry is aware of this and is developing a more appropriate way to characterize the colour quality of LED light sources.

Temperature also affects the brightness and colour of the LED. Phosphor-converted LEDs are sensitive to temperature (Figure 6 and 7). Studies show that, although the LED emission is relatively stable at junction temperatures below 80 °C, higher temperatures cause discolouration of the encapsulating clear plastic and loss in transparency for longer (amber) wavelengths[4]. This results in a colour shift towards the blue over time. It is critical that the temperature of the LED be kept below 80 °C for a long-life operation.

Development Trends in LED Technologies

The phosphor-conversion process is not perfect. Some of the radiant energy from the blue LED is converted to heat within the phosphor causing a shift in the emission characteristics called Stokes loss. A thicker phosphor will increase the amount of blue light that is converted to amber, but the phosphor will get hotter, causing a shift in the colour over time and even destruction of the phosphor layer or other parts of the assembly.

Manufacturers are working on increasing the conversion efficiency of the phosphor and making the chip more tolerant to high temperatures[5] (Figure 8).

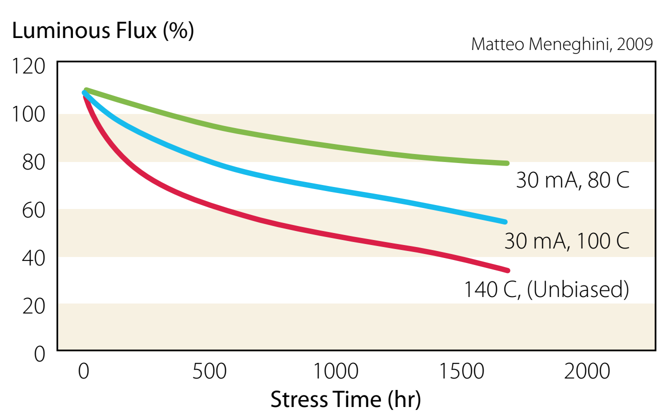

Figure 6 — LEDs operated (stressed) at relatively high temperatures (>80 °C) rapidly lose their brightness as the lens material darkens.

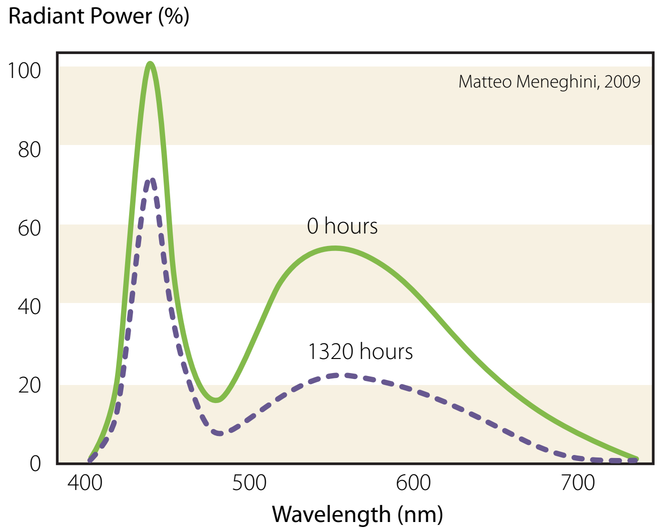

Figure 7 — Operation at relatively high temperatures causes a colour shift in the emitted light over time as the phosphor is degraded by heat.

Currently available products are not much better than modern HID lamps—specifically HPS lamps. The amount of light emitted (lumens) per watt of electricity is called efficacy (lm/W). HPS bulbs peak at about 130 lm/W. As of 2011, the state-of-the-art (in the lab) white LEDs reached efficacies of 100-150 lm/W[6] and a CRI of 80. However, although the performance of HID bulbs has reached their peak, LEDs are still maturing. In the next decade, the performance of LEDs is expected to reach 200 lm/W with a CRI of over 90. The theoretical limit for broadband LEDs is about 250 lm/W[7].

Summary

Although recent LED lighting products are not much better than the current HPS bulbs, they hold great promise to change the nature of artificial lighting. The brightness of the lamps can be relatively easily adjusted and the directionality of the emitted light can more easily be tailored to a specific distribution pattern, thereby reducing glare and light trespass. They can more easily create a uniform illumination pattern, and their light output is more easily controlled. If their sensitivity to temperature can be significantly reduced, LED useful life could eventually exceed that of the current HID bulbs of over 20,000 hours.

As the efficacy of LED luminaires improve, LEDs will allow a significant reduction in the energy used for lighting. This last point will encourage the replacement of old, unshielded luminaires for ones that reduce glare, light trespass, and illumination levels, thereby reducing all forms of urban light pollution, including sky glow. In the future, we must restrain ourselves from squandering the higher-energy efficiencies by illuminating the night landscapes to brighter levels.

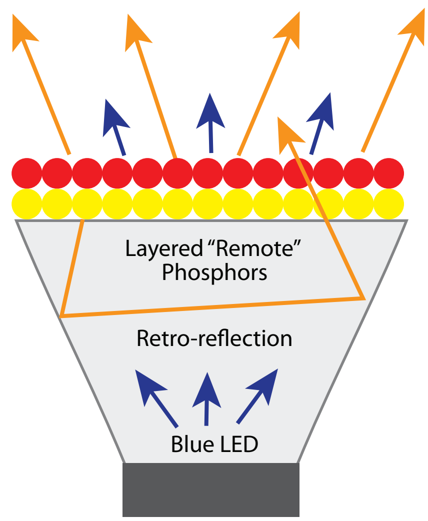

Figure 8 — Two strategies for increasing the efficacy of LEDs are to layer the phosphors in order of increasing emitted wavelength, and use optics to retro-reflect some of the scattered light out of the LED. By keeping the phosphors away from the hot LED chip, the characteristics should last longer.

Acknowledgements:

I thank Nichia Corporation, and in particular Saori Mitsuhashi and Kathy Julian of the Nichia America office, for providing information and answering questions about the LED industry and technical developments.

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International Dark-sky Efforts

– Dr. David Welch
Chair DSAG-IUCN

– Robert Dick
Chair RASC-LPAC

Abstract

For the most part, the early concern about the growth of light pollution (LP) was one for astronomers, but during the last ten years it has become evident that LP affects the environment in fundamental ways. The sharing of information and coordinated efforts are beginning to result in significant change by promoting the issue at the levels of national and regional governments. As astronomers forge more links with the environmental and sustainability movements, light pollution is starting to be controlled and in some places reduced.

Historical growth in international dark-sky efforts

Concern over dark-sky sites dates back to the early 20th century, as astronomers sought locations for their new observatories on mountains in remote areas with inherently more clear nights, better seeing than can be found at lower elevations, and with darker skies that were free of the growing artificial light at night (ALAN).

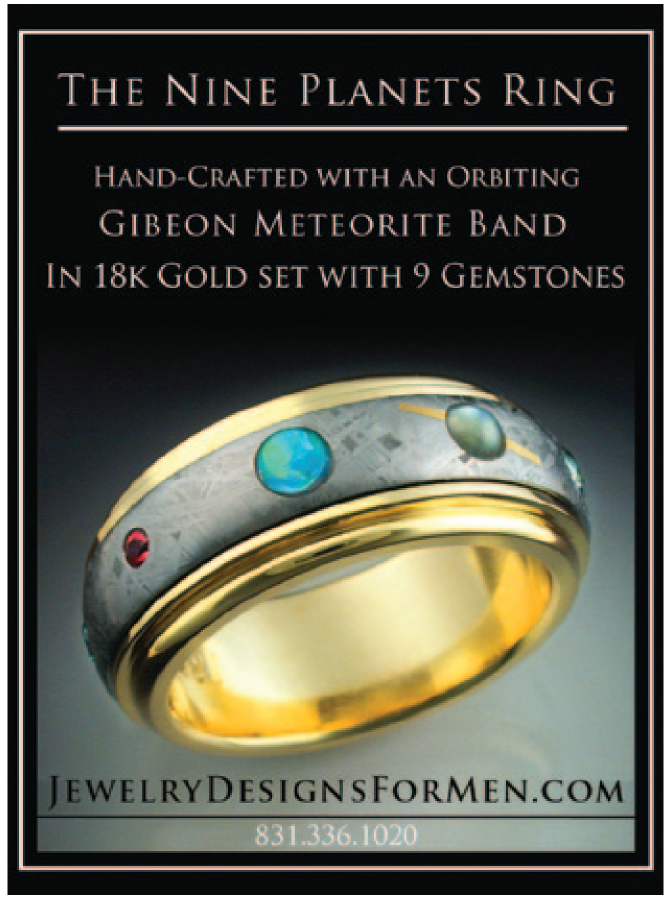
In the case of artificial lighting, the benefits include: the use of marker lights for safe navigation, by pedestrians and motorists to aircraft; extended hours of commercial operations; appreciation of cultural landscapes and heritage buildings after dark; and increased opportunities for outdoor recreation. However, artificial light becomes a problem when the adverse effects exceed the benefits.

Based on our culture, our society must weigh the significance of the benefits against the adverse impacts. These can include: reduced highway and footpath visibility due to glare; increased risks of cancer in humans; disruption of the circadian rhythm; effects on nocturnal organisms or their ecological relationships; and energy wasted as light spills onto neighbouring property or shines directly into the sky. We need some artificial outdoor light at night, but it should be limited to the brightness, colour, time, and area needed in order to minimize its adverse biological and behavioural impacts.

The organizations currently involved with light-pollution abatement wish to protect heritage places, be they national parks, historic sites, or cultural landscapes. The following list of benefits are presented in an order that puts priority on heritage protection, however, in the wider set of benefits referred to above, they are of equal importance. We should limit lighting in order to:

- Preserve the ecological integrity of natural environments,
- Ensure the full enjoyment of a wilderness experience,
- Appreciate the integrity, character, and beauty of rural landscapes,
- Protect and present the authenticity of cultural sites (tangible heritage),
- Help preserve living traditions and ceremonies related to the night,
- Help preserve intangible heritage related to mythology, traditional navigation, and culture,
- Protect human health, both medical and psychological,
- Contribute to energy efficiency,
- Improve personal security through non-glare lighting in urban areas. and
- Benefit professional and amateur astronomy, astro-tourism, and the right to an unpolluted night sky.

To address these concerns we must change the way we view outdoor lighting. Personal efforts can be very helpful to protect local properties, but large areas require the efforts of socially and politically active individuals and organizations.



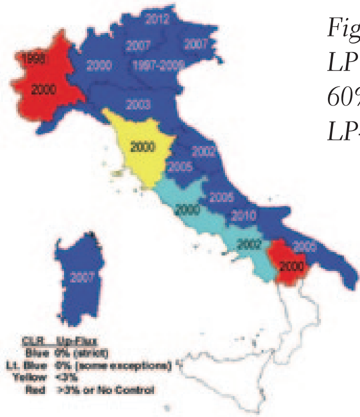


Figure 1 —Adoption dates of LP legislation in Italy[7]. Over 60% of the country now has LP-limiting legislation.

Organizations in various countries and their approaches to LPA

The methods used by organizations to promote dark skies are based on the culture of their country/society and the personality and strengths of the proponents, as well as the nature of the opposition[1].

Knowledge of the causes and solutions to light pollution are important, but having the organizational and political influence is equally, if not more important. Publishing studies on the causes and recommended solutions can raise the profile in academic circles, but rarely do these materialize into concrete action without the determination of individuals willing and able to promote them in government. Without government action, in terms of legislation, there is no impetus for those responsible for lighting to change how light is used. For example, a search on the Internet produces many sites about light pollution, but there are only a few dozen people on each continent lobbying governments to take action.

Europe is a good example of how nationality and the tenacity of individuals affect the nature of a dark-sky program. Most European countries have proponents for light-pollution abatement but the main difference between the LPA policies is due to individual leadership, the national economy, culture, and the aggressive marketing of the lighting companies.

Of all the European Union Countries, only Slovenia, Italy, Croatia, and France are making significant headway in controlling and even reducing light pollution. The Italian effort began in 2000 with the Lombardi Law[2]. This is being adopted region by region. The latest province is Bolzano in the north (Figure 1). The Lombardi Law has been adapted, with improvements by Slovenia, which now has the strongest LP laws in the world[1] (Figure 2). Croatia and France are in the process of developing national legislation. Spain is currently taking a more conservative route by codifying previous standard practice. The other countries have not progressed to the level of legislative control.

Local economies can affect the degree of opposition towards reduced lighting. For example, in countries with smaller economies such as Croatia, the lighting-company lobby may be more aggressive. Companies may fear that reducing light pollution will reduce their sales, so there is strong resistance, whereas in larger economies, the companies have less need to be aggressive. Therefore, we typically see more over-lighting in smaller economies, even though the infrastructure costs are a burden. In other words, the economies that can least afford excessive lighting spend more. This trend can be offset somewhat by a concerted effort to develop a lighting policy and legislation to enforce the policy.

Individuals play major roles. Dr. P. Cinzano, Dr. Fabio Falchi, and others in Italy, have caused the enactment of the Lombardi Law, which includes the use of full cut-off fixtures, puts caps on candela per hectare, and brightness levels.

Smaller and younger countries have the opportunity to benefit from our current understanding of light pollution, and some have leveraged earlier legislation in other countries—formulating very strong laws to place limits on outdoor lighting. Slovenia was able to add deadlines on the conversion to low-polluting light by leveraging the Lombardi Law, thereby accelerating lighting improvements.

The local and national culture affects the use of outdoor lighting, which can either help or hinder light-pollution abatement. The energy use for lighting can help compare

Figure 2 — Reduction in glare and circadian-disrupting white light retains the relaxed village quality of the island of Lastovo, Slovenia, in the Adriatic Sea (images courtesy of A. Mohar, colour adjusted by RD to reflect visual appearance.)

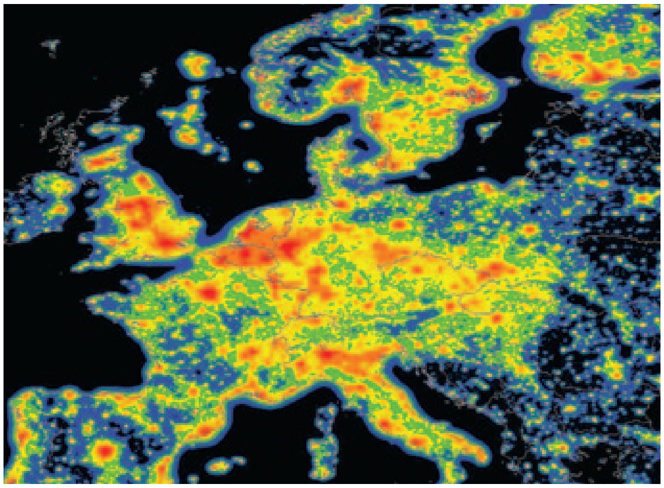


Figure 3 — Sky glow above European Union countries (8). Unlike North America, there are very few areas left to save pristine skies. National European LP programs focus on slowing the growth of LP and guiding their societies toward a more sustainable future.

various cities and countries. Table 1 is a comparative list for some European countries. For example, Graz in Austria uses only 25 kwh/yr per capita for lighting[1]. This can be compared to Ottawa, Canada, which uses approximately 50 kwh/yr per capita (based on 50,000 100-watt street lights with an equivalent amount of energy used for commercial signs and a population of 750,000).

In North America, the International Dark-sky Association, in Tucson, Arizona, was created in 1988 in response to the growing concerns among astronomers over the degradation of the night skies above the national observatories, specifically the large Kitt Peak facility near Tucson, and more generally the impact of ALAN on the visibility of the night sky that was discouraging public stargazing. A similar concern was raised in 1991 by the membership of The Royal Astronomical Society of Canada, which resulted in the development of the RASC Light-Pollution Abatement Program.

These two organizations approach the problem of light pollution in different though complementary ways. The IDA has promoted dark skies for stargazing and astronomy,

Table 1

Country	Lighting Energy per capita (kwh/yr)[1]
Austria	40-50 (estimate)
Belgium	108
Croatia	100
Germany	55 (9)
Italy	108
The Netherlands	40-50 (estimate)
Slovenia	83
Spain	114

while the RASC increases the awareness of how LP impacts animals and human health. Both these programs raise public awareness of light as a potential pollutant.

Faced with relatively inexpensive energy in North America, energy conservation in lighting has not been particularly successful. Benefits from more-efficient light sources have been eroded by the increase in lighting levels. So, although energy savings are important for LPA in Europe, where reduced lamp wattage can save >24% of the power per luminaire, in North America the conversion to FCO fixtures, while maintaining power levels, has negligible energy saving. In most jurisdictions, increasing electric lighting is still considered to be vital to urban lifestyles.

Views from space[3] (Figure 3) show Europe to have extensive artificial sky glow and it is growing at 2-4% per year, so there are very few dark-sky parks in Europe. In contrast, North America has vast areas of nearly pristine skies. Even with strong LPA legislation, it is unlikely Europeans will ever see a dark sky of the quality enjoyed in Canada or the United States. This makes it much easier in North America to protect large rural areas without disrupting the lighting culture of urban areas. Our advocacy in North America is turning against the growth of light pollution in our cities, and we can learn from the policies and efforts of our European colleagues who are currently focusing on urban lighting.

Major characteristics of dark skies that are promoted by organizations

The main actors on a global scale are listed in Table 2. In this table, we include the IDA with its network of international affiliates, and the RASC in Canada for the dissemination of its dark-sky lighting protocol that addresses astronomy, ecology, and human health. In contrast, astronomy is only a peripheral benefit in the USNPS, UNESCO Astronomy and World Heritage, IIADSP, and IUCN-DSAG.

The list in Table 2 underscores the fact that not all dark-sky programs focus on astronomy. They address different aspects of environmental protection and nocturnal darkness. There are two ways dark-sky programs can be used by organizations without an astronomical mandate.

First, it can be used as a new component in a package to help market the region as a destination for eco-tourism.

National parks have the mandate to provide a means for the public to visit and experience nature. In the United States, the National Park Service Organic Act of 1916 recognizes the need to protect the natural environment for the present and the future[4]. The American statistics suggest a levelling off in visitors over the last 15-years or so[5]. Some reporters and bloggers suggest this is due to the popularity of videogames.

Table 2

Programs in National and International Organizations working towards the reduction in Light Pollution

Date	Organization*
1988	***International Dark-sky Association***
1991	***Royal Astronomical Society of Canada Light-Pollution Abatement Program***
1999	***US National Park Service (USNPS) Natural Sounds and Night Skies Program***
2005	***RASC Dark-Sky Preserve and Urban Star Park Program***
2005	UNESCO Astronomy and World Heritage Initiative
2007	***IDA Dark-Sky Parks, Reserves, and Communities Programs***
2007	Starlight Initiative – Starlight Conferences and Declaration
2008	***Initiative for an International Association of Dark-Sky Parks (IIADSP)***
2009	***International Union for Conservation of Nature – Dark Skies Advisory Group***
2010	UNESCO World Heritage thematic study on archaeoastronomy.

* Organizations in ***bold italics*** focus only on dark-sky issues. Other organizations have broader mandates that also include light pollution.

Promoting dark skies as an aspect of eco-tourism has been suggested to help increase attendance.

Similarly, the current National Park system in Canada[6] addresses the need to protect natural areas, but the USNPS and the Parks Canada Mandates do not refer directly to the night sky.

The RASC Dark-Sky Preserve Program has been used to help increase the attendance in the National Parks as part of their eco tourism plan. Though some new DSPs did show increases in attendance, it does not guarantee more visitors[6]. Attendance also depends on promoting the parks and their new programs to the large non-park-going public. This is usually not done very well because of the centralized nature of Parks Canada and the very limited advertising budget of most individual parks.

A second component to using dark skies is to combine astronomy with other cultural attributes in order to protect a region from modern development. The current tack of the UNESCO World Heritage Site program is to get astronomy recognized as one of the potential "outstanding universal values" that a place needs in order to become a World Heritage site. Dark sky, astronomy, and links to archaeoastronomy may "tip-the-scales" for an area in the recognition as a World Heritage Site.

The dark skies of a region could be a component in support of the establishment of an aboriginal heritage site. Heritage site recognition focuses on retaining the visual culture of a region by preserving the architecture that may include promoting the visual icons by increasing accessibility. Artificial outdoor lighting can be used to encourage visitors in the evening while providing visibility for security after hours. However, promoting the cultural value of a dark sky provides a restraint on excessive lighting, while expanding on the cultural link to nature.

Summary

A Light-Pollution Abatement Campaign must reflect the country's culture, economy, and regional context. A campaign must also be driven by individuals who can work with the government to effect change. As with other forms of pollution, corporate profits should not be used to override the need for a healthy environment.

The establishment and protection of heritage sites can take advantage of dark skies, astronomy, and related sciences to help establish and maintain these sites.

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Mont-Mégantic First International Dark-Sky Reserve: Achievements And Challenges

– Sébastien Giguère

Science education director, ASTROLab du Mont-Mégantic

Five years ago this fall, the first International Dark-Sky Reserve was created in the Eastern Townships in Québec. Officially certified in September 2007 by the IDA (International Dark-Sky Association) and the RASC (The Royal Astronomical Society of Canada), the Mont-Mégantic International Dark-Sky Reserve (RICEMM) covers a territory of 5,500 km^2, including two RCMs (Regional County Municipalities), as well as the City of Sherbrooke. It unites 35 municipalities and over 225,000 citizens.

Led by the ASTROLab, a public outreach centre, with the help of numerous partners such as the Mont-Mégantic Observatory and National Park, this world-premiere site is the result of a combined regional effort. Focus was on four areas: awareness, regulation, lighting conversion, and monitoring. Besides having given back the observatory and the region a darker sky, the creation of the reserve, with the conversion of over 3,300 light fixtures, also reduced power consumption on its territory by about 9,500,000 kWh over 5 years, which represents energy savings close to $1,000,000.

Despite the initial success of the reserve, the ASTROLab had to re-launch its light-pollution abatement project in 2011 in order to curb the installation of non-compliant light fixtures, which causes the quality of the night sky to deteriorate and poses a risk to the sustainability of the reserve itself. The recent massive introduction of LED (Light-Emitting Diode) lighting, with all of its advantages and drawbacks, also represents a major new challenge. Advice and expertise have been sought by city authorities on this issue, and ASTROLab managers are presently working on finding solutions to improve and monitor this type of lighting. A symposium on this problem is being organized and will take place in Sherbrooke, Québec, this coming December.

Back in 2003, the initial phase of the light-pollution abatement project was primarily focused on Observatoire du Mont-Mégantic (OMM) scientific sustainability. The OMM is one of the best-instrumented University Research Centres in the world. It houses a 1.6-metre telescope, which is the third largest in Canada. The Observatory has the darkest sky of all research observatories in Canada, which makes it one of the best facilities in the country. However, at the turn of the millennium, members of the Québec astronomical community estimated that light pollution at the top of Mont-Mégantic had more than doubled since the opening of the Observatory. The problem was getting worse, and people were starting to worry for its future. Furthermore, the closing of the OMM would be a major loss, not only for the science of astronomy in Québec and Canada, but also for an entire region, which has developed an important part of its tourist identity based on the darkness of its starry sky. Managed by Mont-Mégantic National Park, the ASTROLab has in fact become a must-see regional tourist destination, attracting thousands of visitors each year—quite an achievement for a site located a long way from major metropolitan areas.

Several initiatives emerged to work toward a solution, and these efforts finally gathered around the ASTROLab project. The action plan identified many objectives: a) to recover the site's original night-sky quality, b) to reduce energy consumption, c) to improve nocturnal environment comfort and safety, d) to reduce the impact of artificial lighting on ecosystems and human health, and e) to increase the pre-eminence of the Observatory, the ASTROLab, the National Park, and the region by giving them special status.

Developed in collaboration with numerous partners, the project was aligned with the regional environment and has succeeded in obtaining financing from government funds dedicated to energy efficiency. Natural Resources Canada and Hydro-Québec provided the primary financing sources for the project, in addition to the contributions of many regional partners. One of the main characteristics of the project was an emphasis on joint action as the core of the approach, plus taking into account the needs of all parties involved. This multilateral approach started to show results in 2005 with the adoption of a lighting regulation by RMC of Granit, followed in 2006 by RMC of Haut-Saint-François, and in 2007, by the City of Sherbrooke.

It was also at that time that the conversion program unfolded, a distinctive feature of the ASTROLab project. While other light-pollution abatement projects have been undertaken before, this one was, to our knowledge, the first that resulted in a massive and immediate replacement of lighting fixtures of municipalities, businesses, industries, and private houses. In 2007, local municipalities converted their street lighting to less powerful but higher-performing fixtures, decreasing light pollution considerably and improving the quality of the nocturnal environment. Many residents in villages simply did not notice that the street lighting had been modified, which shows clearly that it is possible to limit light pollution and energy waste without compromising comfort and security. Impact on the night sky was immediate and impressive, exceeding even the expectations of the project

Caption: La Patrie village before and after the ASTROLab conversion project. The village is located directly at the base of the mountain. — ASTROLab, Guillaume Poulin

initiators. "We no longer see a light dome over these municipalities when clouds cover the sky. And, we have to get back to our old habits and use our old flashlights when we walk around the observatory. It's really amazing!" explains Bernard Malenfant, OMM technician and founding president of the ASTROLab. A few months later, Chloé Legris, the project leader, was awarded the Scientist of the Year title by CBC-Radio-Canada in Québec.

Light-pollution reduction generated through all these efforts was evaluated at 35% at zenith in 2009, compared to levels before the program began. This measurement was compiled by Professor Martin Aubé and the GRAPHYCS research group at the Cégep de Sherbrooke, who are responsible for the scientific follow-up of the project. Renowned as a leading expert in light-pollution measurement, Professor Aubé recently carried out the installation of two complementary measuring instruments on the roof of ASTROLab: the SAND-2 spectrometer and the wide-band photometer LPRad-1, both conceived and developed specifically for this type of follow-up. He also developed a numerical model able to produce contribution and sensitivity maps for a particular site sky.

Increase of public awareness, notoriety, and regional pride has also exceeded expectations. Calls from across the globe have been received to share Mont-Mégantic's experience and expertise for other projects. RICEMM managers have welcomed numerous visitors who came to learn by experience, such as Steve Owens, project leader for Exmoor National Park International Dark-Sky Reserve in England and Nicolas Bourgeois, project leader for the future Pic du Midi de Bigorre Reserve in France. Complementing the ASTROLab site, the Dark-Sky Reserve significantly helps the Observatory to take roots in its environment and increases the sense of belonging of local residents towards the Observatory. When OMM budget cuts were announced in 2009, threatening its operations, regional reactions and mobilization around the Observatory and the Reserve were so strong that they contributed to bringing about a political solution to the problem.

After a few years though, the initial euphoria has been replaced with worries. The reappearance of light fixtures that do not comply with regulations has been noticed. It appeared that the sustainability of the Dark-Sky Reserve was not secured. In 2011, faced with the progressive deterioration of the night sky, the ASTROLab has set about re-launching the light-pollution abatement project. Elected officials and stakeholders in the reserve territory were invited to recommit in order to protect RICEMM. A new action plan was established, focusing mainly on improving the enforcement of regulations at the municipal level and on the availability of compliant fixtures with the distributors. Committees for the preservation of the night sky were created in each RMC and in the City of Sherbrooke, each targeting context-specific priorities. Motivated by this re-launching, the reserve managers quickly realized that they had underestimated a potentially bigger threat: the massive and uncontrolled arrival of white LED lighting.

In a few years from now, LED lighting will have become one of the primary, if not the main, lighting technologies in the world. This technology offers unique advantages: low energy consumption (comparable to high-pressure sodium (HPS) lamps), controllability, colour rendition, and long life span. These benefits ensured that conversion funding is now available in Québec to encourage municipalities to replace HPS equipment by LED light fixtures, and this nearly happened right in the reserve territory.

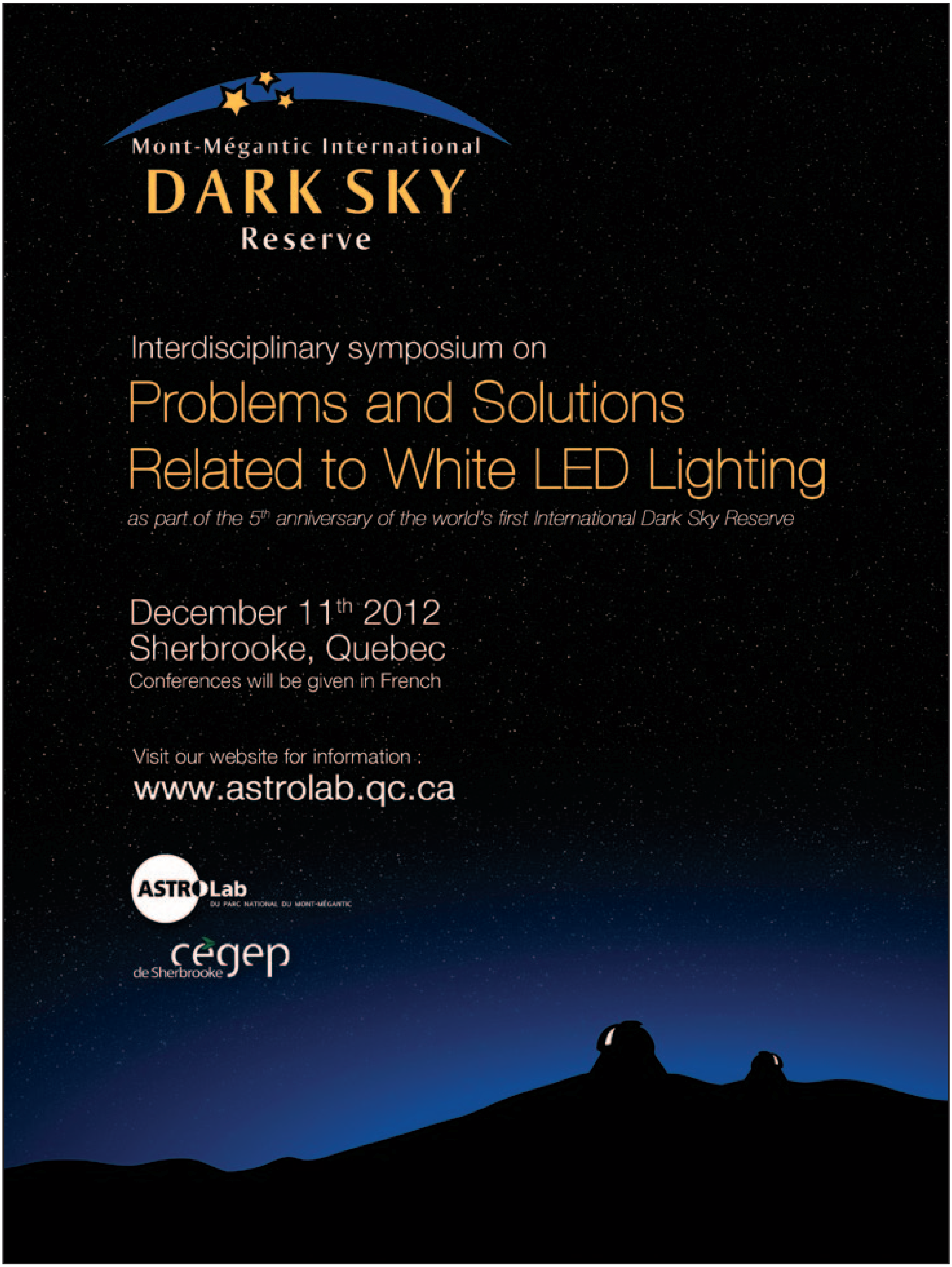
The threat represented by white LED lighting for light pollution is due to the fact that this technology will emit a significant fraction of its light in the blue portion of the spectrum. Since the atmosphere preferentially scatters blue light, and our scotopic (nocturnal) vision's maximum sensitivity is located within that same region of the spectrum, the impact of a white LED fixture on light pollution is much bigger than that of a high-pressure-sodium fixture, whose peak emission is in the yellow-orange portion of the spectrum. Professor Aubé estimates that each LED light fixture installed on the reserve territory would reverse positive gains obtained from the conversion of eight light fixtures (in the reserve, cobra-head fixtures were replaced by Helios, along with a 50% reduction of lamp power). It's easy to understand the extent of what is at stake.

Furthermore, in the last decade, the major impact of blue light on melatonin suppression, the "sleep hormone" that regulates our biological clock, has been better documented, leading to a greater awareness of its importance for human health. The World Health Organization now classifies circadian disruption as a probable human carcinogen. Some studies estimate that as much as 30% of breast cancers could be a result of such disruptions. In Israel, research has shown a strong correlation between breast-cancer rates and light-pollution level. Other impacts of blue light and melatonin suppression have recently been identified: stress, insomnia, depression, thermoregulation, alertness, and heart rate. This field of study still remains in an early stage and some caution needs to be exercised, of course, but up to now, most indicators lead in the same direction: melatonin is fundamentally important for human health, and nocturnal blue light, even at low levels, is disruptive to the secretion of this hormone.

Observatoire du Mont-Mégantic and light pollution on the horizon. – Parc national du Mont-Mégantic / Guillaume Poulin

The arrival of the LED revolution has upset the RICEMM strategic plan. In view of these disquieting findings, the ASTROLab and its allies have joined forces with many partners from the scientific world and the industry to get a better understanding of the issues related to these light fixtures and, more importantly, to get involved in developing solutions that would minimize negative impacts. The initial phase of this new mobilization will take concrete shape in December 2012, with the organization of a symposium on "problems and solutions related to white LED lighting." Invited participants include panelists from a variety of backgrounds: physics, chemistry, medicine, urbanism, industry, government, *etc*., as well as representatives from the ASTROLab, OMM, RASC, and IDA. The symposium will make it possible to present work and studies done by different stakeholders and specialists; several kiosks will also demonstrate different technical solutions proposed to reduce the negative effects of white LED.

In keeping with the ASTROLab approach, stakeholders intend to work in a spirit of cooperation and joint action, to promote development and deployment of lighting solutions that are capable of addressing the needs of society, while also meeting dark-sky, health, and environmental concerns.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Dark-Sky Parks

– Dr. David Welch
Chair DSAG-IUCN

– Robert Dick
Chair RASC-LPAC

Abstract

The dependence of the ecosystem on dark nights is discussed elsewhere in this issue, and its specific impact on a number of animal species is well reported in the literature, for example. Dark skies can be used to expand the concept of eco-tourism and to gain protection for heritage sites. Given the close dependence of ecosystems upon natural darkness, it follows that all protected natural areas, henceforward collectively referred to as parks, should include the protection of natural darkness as part of their management goals. Solving the problem of light pollution *in situ* is a "low-hanging fruit" in policy-speak. Restoring and maintaining natural darkness within a park can be achieved unilaterally and at relatively little capital cost. It requires no up-front local research, it produces ecological and visitor enjoyment benefits almost immediately, and it demonstrates easy-to-understand best practices for energy efficiency and sustainable development.

A brief history of dark-sky parks

As a means to promote the awareness of light pollution, a number of organizations have established programs to recognize areas being protected from light pollution. This initiative began in 1993 with the first, though temporary, dark-sky park in Michigan, which was followed in 1999 by the establishment of a permanent site in Ontario (Torrance Barrens Conservation and Dark-Sky Reserve). The Torrance Barrens area became the world's first park to be assessed and recognized as a dark-sky park by an independent authority, The Royal Astronomical Society of Canada (RASC). Also in 1999, the United States National Park Service established its Natural Sounds and Night Skies Program, seeking to secure dark skies and night-sky viewing in its national parks.

In 2005, the RASC established a formal program to confer dark-sky status on other parks, using the term Dark-Sky Preserve. As of June 2012, the RASC has recognized 14 Dark-Sky Preserves and one Urban Star Park.

In 2007, the International Dark-Sky Association (IDA) started its International Dark-Sky Places program, with three classifications. As of June 2012, there are ten IDA International Dark-Sky Parks, five International Dark-Sky Reserves and four International Dark-Sky Communities.

What it means to be a dark-sky park

The International Union for Conservation of Nature (IUCN) recognizes six categories of protected areas, such as strict nature reserves, national parks, or sustainable use of natural ecosystems. Common to all is a management goal of balancing the protection of natural features, ecosystems, and landscapes with the enjoyment and appreciation by present and future generations of people, and, in some cases, sustainable development through conservation of resources. All these mean that management practices should include the abatement or removal of environmental stresses, either through direct action within the park or reserve, or indirectly through lobbying of, and cooperation with, stakeholders in the greater park ecosystem, and in broader jurisdictions such as state, province, and nation.

Light pollution is one stress in many parks and reserves, although, as noted above, not usually as severe as some stressors such as air and water pollution, or resource extraction, *etc*. However, light pollution is an issue that can be solved locally by direct action, and regionally by stakeholder cooperation.

Both the IDA and RASC have the following requirements for their dark-sky programs. A dark-sky park is a protected natural area or cultural site with both:

- Protocols and practices for light-pollution prevention within the park, such as plans, guidelines, darkness monitoring, enforcement, restoration of darkness; and
- Outreach and cooperative agreements within the view-shed, to reduce sky glow and light trespass into the park.

Being naturally dark does not in itself signify that a park qualifies as a dark-sky park. Many protected areas in regions of extensive remote wilderness would otherwise qualify automatically. Rather, a management document should address various aspects of restoring, preserving, and presenting values associated with naturally dark skies. Such a document may be a park management plan or legislation by the appropriate level of government. Communities within parks should have their own outdoor lighting objectives and plans.

Outdoor lighting standards and guidelines for parks were developed for Parks Canada and are available from the RASC. Solutions are offered for a variety of typical park situations, such as management and visitor-centre buildings, parking lots, roadways and pathways, campgrounds, historic sites, and signs.

Of equal importance to outdoor lighting management is the provision of visitor opportunities to appreciate an unpolluted night sky, an ecosystem free of artificial lighting at night, and historic sites presented in an authentic state. Visitor engagement should blend night ecology talks and related cultural traditions and myths and hikes with wilderness astronomy. This may involve: night-sky talks that address the night sky as may be seen by visitors, and myths; star parties; static displays and travelling planetaria; and audio-visual presentations on nocturnal ecology.

In addition to bringing night-sky and ecology appreciation to visitors, a dark-sky park should attempt to disseminate these values and practices to a wider audience. This may involve cooperating with the media, be it in print, broadcast, Internet, to demonstrate the importance of preserving a natural night sky and to illustrate the experiences this may offer.

Research and monitoring of the ecology of the night, or scotobiology, should be conducted. This may be done directly, where resources allow, or through cooperation with universities and research institutions. Protected areas can be used as benchmark laboratories to study natural systems and to compare them against more stressed areas to better determine the impacts of light and other environmental stressors. Citizen-scientists could contribute to such research by gathering data while appreciating the nocturnal environment.

With several independent organizations conferring designations on dark-sky parks, the terminology can be confusing, though the requirements tend to be similar.

The RASC created two designations in 2005: Dark-Sky Preserve and Urban Star Park. A RASC DSP is an area in which no artificial lighting is visible, and which incorporates active measures to educate and promote the reduction of light pollution to the public and in nearby municipalities in order to help protect the site into the future. The RASC USP defines an area in which artificial lighting is strictly controlled and with similar outreach programs. However, it is understood that sky glow from beyond the borders is the main source of light pollution over the park.

An IDA International Dark-Sky Park is a park or other public land possessing exceptional starry skies and natural nocturnal habitat where light pollution is mitigated and natural darkness is valuable as an important educational, cultural, and scenic and natural resource. It identifies and honours protected public lands with exceptional commitment to, and success in implementing, the ideals of natural night preservation and/or restoration.

An IDA International Dark-Sky Reserve (IDSR) combines both public or private land possessing exceptional starry nights and a nocturnal environment that are protected for their scientific, natural, educational, cultural, heritage, and/or public enjoyment. It contains a core area meeting minimum criteria for sky quality and natural darkness, and a peripheral area that supports dark-sky values in the core and receives benefits from them as well. It involves a partnership of multiple landowners and/or administrators that recognize the value of a starry night through regulation and/or formal agreement and/or long-term planning. The IDSR idea is configured and operates similar to a UNESCO biosphere reserve, as it promotes dark-sky values within communities, not just natural areas.

An IDA International Dark-sky Community is a town, city, municipality, or other legally organized community that shows exceptional dedication to the preservation of the night sky through the implementation and enforcement of quality lighting codes, dark-sky education, and citizen support of dark skies.

Astronomical associations in several European countries have also declared a number of areas to be dark-sky parks. The full world list is presented in Table 1 with their geographical and management information. This list is maintained by Dark Skies Advisory Group of the IUCN (DSAG-IUCN) and the Web site is hosted by the Initiative for an International Association of Dark Sky Parks, based in Slovenia.

Summary

Dark-sky protection is an emerging and growing movement. Concerns over energy efficiency, human health, ecological impacts, and the right to see the stars resonate with many people in many countries. These areas are both protectors of natural ecosystems and places for the demonstration of best practices. Protected areas find a natural fit with light-pollution abatement, with visitor activities aimed at the appreciation of the night environment.

The main impetus for adding dark-sky protection to parks and reserves came from North America with The Royal Astronomical Society of Canada and the American-based International Dark-Sky Association. There are now 37 dark-sky parks and reserves worldwide. Twenty-four are in North America, but this imbalance is expected to diminish over the next few years as other countries, particularly in the Southern Hemisphere and in Europe, add dark-sky management practices to their protected natural and heritage areas.

North America and southern nations have an advantage in creating dark-sky parks, in that these regions have large areas with very low population densities, so natural wilderness areas free from sky glow are easy to find. This is far from the case in Europe and southeast Asia. In these situations, light pollution relates primarily to regional sky glow, rather than in-situ lights. While dark-sky parks are an excellent means to promote the idea of night-sky protection, the ultimate solutions must come from better lighting practices in urban areas.

In this context, the dark-sky park idea is the preferred way for currently protected areas to proceed; either as a formal reserve or functioning as one through regional cooperation among communities and land managers. Urban star parks or suburban astronomy outreach sites can also become elements in reducing light pollution. They may not be dark enough for astronomy, but they will be where the greatest number of people would be won over.

Table 1

Dark-sky Parks of the World, June 2012

Country	Name	Centroid	Area (ha)	Date
Canada	Beaver Hills DSP	53.6, -112.9	29,300	2006
	Bruce Peninsula DSP	45.2, -81.5	16,700	2009
	Cypress Hills DSP	49.7, -110.2	39,600	2005
	Fundy DSP	45.6, -65.1	20,600	2011
	Gordon's Park DSP	45.7, -82.0	108	2008
	Grasslands DSP	49.1, -107.4	52,700	2009
	Irving Urban Star Park	45.2, -66.1	243	2011
	Jasper DSP	52.9, -118.0	1,122,800	2011
	Kejimkujik DSP	44.4, -65.2	40,370	2010
	Kouchibouguac DSP	46.8, -65.0	23,920	2009
	McDonald Park DSP	49.1, -122.2	2,225	2003
	Mont-Mégantic IDSR and DSP	45.5, -71.2	5,845	2007
	Mount Carleton DSP	47.4, -66.9	17,427	2009
	Point Pelee DSP	42.0, -82.5	2,000	2006
	Torrance Barrens DSR	44.9, -79.5	1,990	1999
Czech Rep.	Izera Dark Sky Park	50.8, 15.3	3,600	2009
Hungary	Hortobágy Starry-Sky Park	47.6, 21.1	82,000	2011
	Zselic Starry-Sky Park	46.4, 18.3	9,042	2009
Namibia	NamibRand IDSR	-25.1, 16.0	172,200	2012
New Zealand	Aoraki/Mackenzie IDSR	-43.6, 170.25	70,696	2012
Poland	Izera Dark Sky Park	50.8, 15.4	3,850	2009
Slovakia	Poloniny Dark Sky Park	49.0, 22.4	48,519.0	2010
Spain	Fuerteventura Starlight Reserve	28.44, -14.10	60,517.0	2009
	La Palma Starlight Reserve	28.71, -17.86	18,627.0	2011
	Monfragüe Starlight Reserve	39.82, -5.94	18,118	2011
	La Rioja Biosphere Reserve SR	42.01, -2.01	5,983	2011
United Kingdom	Exmoor IDSR	51.14, -3.65	69,200	2011
	Galloway Forest Dark Sky Park	55.1, -4.4	77,700	2009
United States of America	Big Bend IDSP	29.2, -103.2	324,219	2012
	Cherry Springs DSP and IDSP	41.7, -77.8	19	2000
	Clayton Lake IDSP	36.6, -103.3	231	2010
	Goldendale Observatory IDSP	45.8, -120.8	2	2010
	Headlands IDSP	45.8, -84.8	242.8	2011
	Lake Hudson Rec'n Area DSR	41.8, -84.3	890	1993
	Natural Bridges IDSP	37.6, -110.0	3,091	2007
	Observatory Park IDSP	41.6, -81.2	418.4	2009
	Potawatomi DSP	41.2, -86.1	129	2009

Notes

Area:
the existing protected area(s) within the dark-sky place, not the dark-sky place itself since some dark-sky places are reserves with notional, not formal, boundaries that encompass a much larger area.

Abbreviations:
DSP: Dark-Sky Preserve. DSR: Dark-Sky Reserve. IDSR: International Dark-Sky Reserve. IDSP: International Dark-Sky Park. SR: Starlight Reserve.

Location:
decimal latitude/longitude.

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