At the junction between day and night lies twilight—one of the most optically rich and aesthetically pleasing times to observe the sky. In deep twilight, long after the sun has set or before it has risen, a fortunate observer can be treated to a startling visual display when clouds appear suddenly, shining in the dark.

Night-Shining

Joseph A. Shaw

Noctilucent clouds observed in the north-northeast sky before sunrise, July 16, 2009, 4:40 a.m. MDT (1040 UTC, 10.4° solar depression angle) from east of Bozeman, Mont., U.S.A. (45.5° N, 111.0° W). Photo information: Nikon D300 at ISO 400, Nikkor 20-mm lens at f/2.8 for 1/2 s.

Photo by Joseph Shaw

Clouds

Noctilucent, or night-shining, clouds are bluish-white, wispy clouds that are seen only at night, particularly during deep twilight. Although noctilucent clouds (NLCs) are often described as appearing after sunset, they can also show up well before sunrise. For example, the photo on the opening spread shows NLCs photographed an hour and a half before sunrise, at 4:40 a.m. Mountain Daylight Time (MDT) (1040 UTC) on July 16, 2009, east of Bozeman, Mont., U.S.A. (45.65° N, 111.01° W), with the sun 10.4° below the horizon.

While I am typically far more likely to photograph the sky at night than early in the morning, this was a special morning. I was hoping for NLCs to appear in the north-northeast sky over the Bridger Mountains because, only six hours earlier, I had captured them for a surprising second night in a row.

The first NLCs were reported in Europe in 1885, two years after the eruption of Krakatoa—indicating a possible connection between NLCs and the volcano.

Summer is the season for NLCs, when the upper atmosphere is coldest. Somehow, the summer of 2009 produced an unusually large number of NLC sightings at latitudes much lower than the usual range of approximately 50–60°. Observations of delicate swirls and feathery bands of silvery clouds in the late-night or early-morning sky were reported over Europe (much of which is above 50° N latitude) and Canada, but also over a surprisingly large number of lower-latitude U.S. locations. For example, during a dramatic outbreak in mid-July 2009, the Space Weather website (www.spaceweather.com) posted NLC photographs from Washington, Oregon, Idaho, Montana, South Dakota, Wyoming, Colorado and Nebraska at latitudes ranging from 41.5° to 48.0° N.

The first NLCs were reported in Europe in 1885, two years after the eruption of Krakatoa—indicating a possible connection between NLCs and the volcano. The first North American sighting was in 1933 and the earliest known reports of NLCs below 45° latitude in North America are in North Dakota in 1993 and frequently in subsequent years, northern Utah in 1995 and 1999, and Montana in 1997. It is unknown whether NLCs existed before 1885 or whether they are beginning to appear with increasing frequency at lower latitudes. There is most definitely a dramatic rise in reported low-latitude NLC observations in the last two decades, but this could also result from more informed observers and better reporting opportunities.

Regardless of latitude, NLCs are best seen when the sun is approximately 9–12° below the horizon, during nautical twilight when only the very upper reaches of the atmosphere are illuminated by sunlight. Near 45° latitude, this corresponds to a short time period approximately 1–1.5 hour after sunset or before sunrise. It also might be possible to see NLCs for solar depression angles in a broader range of approximately 6°–15°, through nautical twilight and into the beginning of astronomical twilight. (See the sidebar for definitions of various forms of twilight.)

Different types of twilight

- *Civil twilight* refers to when the sun is 6° or less below the horizon (it ends at sunrise). When it occurs, artificial lighting is required to read, and bright stars and planets are visible in the sky.
- *Nautical twilight* occurs when the sun is 6°–12° below the horizon. It is possible to navigate by stars at this time with reference to the visible horizon.
- *Astronomical twilight* refers to the period when the sun is 12°–18° below the horizon. The sky appears totally dark to most observers; by the end of astronomical twilight, the sun no longer illuminates any of the atmosphere and all astronomical observations are possible.

Approximate latitudes for selected world cities

65°	Fairbanks, Alaska, U.S.A.	Oolu, Finland
57°	Aberdeen, Scotland	
55°	Moscow, Russia	Ushuaia, Argentina
53°	Edmonton, Canada Dublin, Ireland	Manchester, England Berlin, Germany
51°	London, England Prague, Czech Republic	Calgary, Canada
47°	Paris, France Quebec City, Canada	Seattle, U.S.A.
45°	Lyon, France Milan, Italy	Ottawa, Canada Dunedin, New Zealand
43°	Florence, Italy Christchurch, New Zealand	Sapporo, Japan Boston, U.S.A.
41°	Chicago, U.S.A. Istanbul, Turkey	Rome, Italy
40°	New York, N.Y., U.S.A.	Boulder, Colo., U.S.A.

NLCs are formed by high-altitude optical scattering

NLCs form at or near the mesopause, the coldest region of the atmosphere, at temperatures near -100°C and altitudes of 80–85 km. This is drastically higher than the highest conventional clouds or even high-altitude bands of volcanic dust, all of which are restricted to the lowest 20 km or so. In fact, it is nearly at the bottom of the near-space region where the aurora shines in the high-latitude night sky.

1047-6938/10/06/0020/6-$15.00 ©OSA

High cirrus clouds lit with nearly full-spectrum sunlight and cumulus clouds lit by reddened sunlight (Aug. 22, 2009, 8:15 p.m. MDT, 0.27° solar elevation angle).

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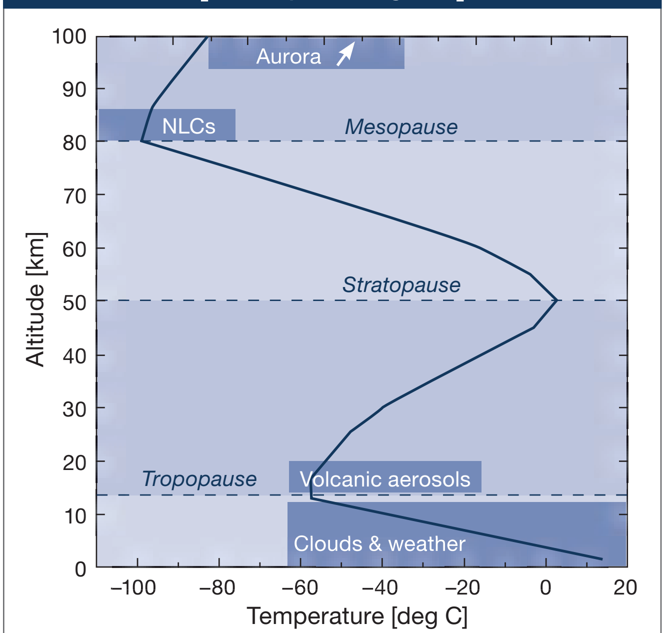
Although there are numerous open questions about the physics and chemistry of NLCs, they appear to be made of water ice crystals nucleated on submicrometer particles of meteoric dust (e.g., iron and nickel). These particles vary widely in size, but they generally have a lognormal size distribution with peak effective diameters near 100 nm (and refractive index near 1.3 for visible wavelengths).

Scientists don't fully understand how a sufficient amount of water vapor makes its way to such extreme altitudes to grow an ice cloud. Some vapor certainly rises all the way up from the troposphere (lowest region of the atmosphere), while some is believed to be formed by the dissociation of methane.

In fact, researchers are particularly interested in the recent apparent increase of low-latitude NLCs because they think it may indicate that the atmosphere itself is changing. Increased carbon dioxide that warms the troposphere could cool the mesosphere, while more methane could lead to a rise in mesospheric water vapor through dissociation, leading to more frequent saturation of air with respect to ice, and consequently more frequent NLCs in the rarified atmosphere near 80 km altitude.

[Atmospheric regions]



NLCs exist in the mesopause, near the 80-km altitude. They are closer to the auroral zone than to conventional clouds.

NLC water ice crystals scatter light without drastically altering the solar spectrum, leading to a fairly white color. The bluish cast of NLCs arises in part because the incident sunlight passes first through a relatively long path of rarified atmosphere that includes the ozone layer between approximately 15 and 50 km. Absorption by ozone removes violet and yellow-red light, leaving a blue-enhanced light to illuminate the NLC particles that are large enough to scatter without strong spectral dependence.

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This "bluing" by absorption in a long, rarified atmospheric path is different from the reddening of light through the scattering of sunlight by atmospheric molecules in the denser, lower atmosphere (molecular scattering has a strong wavelength^{-4} dependence). The sunset picture above is an example of the short-wavelength light that has been depleted by scattering along the long atmospheric path to low-altitude clouds at the bottom of the photograph.

Noctilucent clouds became visible more than an hour after sunset on July 14, 2009. North-northwest view at (left) 9:39 p.m. MDT (0339 UTC, 4.8° solar depression angle) and (right) 10:35 p.m. MDT (0435 UTC, 12° solar depression angle). Nikon D300 at ISO 800, Nikkor 18-200 mm lens at *f*=40 mm at (left) f/4.5 for 1/60 s, (right) f/2.8 for 2 s.

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Notice also the relatively white cirrus clouds at the top of the picture (probably near 10 km altitude), which are illuminated by light that traverses a shorter atmospheric path than the one to the lower clouds. For both the high and low clouds in this photograph, the optically large cloud particles (typically 1-100 μm) scatter without significant wavelength dependence—which means the clouds act as a fairly neutral screen that shows the colors remaining in the incident sunlight. Eventually, the sun will drop sufficiently low to put the low clouds in shadow while still, if only briefly, illuminating the high clouds with sunset colors.

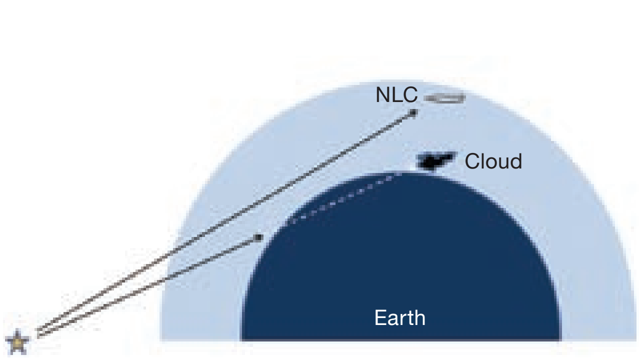
A similar geometrical argument (see diagram below) explains why extremely high-altitude NLCs shine so long after the sun sets or before it rises. At that time, the vast majority of the atmosphere and all conventional clouds (even "high-altitude" cirrus) are in darkness, but the NLCs are illuminated directly. These ultra-high clouds typically are not even visible against the sky unless the sun is at least 6° below the horizon because they are so optically thin. Their optical thickness (path-integrated extinction) is often of the order of 10^{-4} to 10^{-7} (i.e., light traversing the cloud undergoes extinction of $e^{-\tau}$, where τ = optical thickness ~ 0.0001).

The best time to observe NLCs is from late May into August in the northern hemisphere and from November into February in the southern hemisphere.

Such incredibly small optical thickness simply does not generate enough scattered light to make NLCs visible until the sky is in near total darkness. But at that time they can be stunning to behold. (For reference, daytime cirrus clouds are considered "subvisual" when their optical thickness is below approximately 0.05, and visual cirrus clouds have optical thickness up to 1 or 2.)

The pair of photographs above shows how a sky with very little hint of high-altitude clouds 28 minutes after sunset (left) became dark enough an hour later to showcase the NLCs that were there all along (right). These photos were taken looking north-northwest on the evening of July 14, 2009, the first of two sequential nights with widely observed mid-latitude NLC displays. The earlier photograph was taken at 9:39 p.m. MDT (0339 UTC) with the sun 4.8° below the horizon, while the later photograph was taken at 10:35 MDT (0435 UTC) with the sun 12° below the horizon. The sun set at 9:11 p.m. MDT (0311 UTC).

[Why NLCs shine so long after sunset]



Noctilucent clouds (NLC) exist very high in the atmosphere, where they are illuminated long after sunset or long before sunrise.

Observing noctilucent clouds

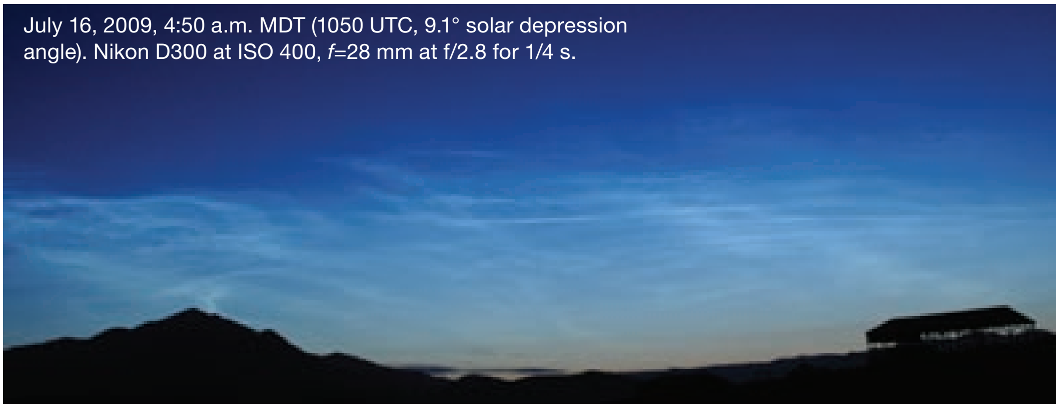
The best time to observe NLCs is from late May into August in the northern hemisphere and from November into February in the southern hemisphere. NLCs are most likely to be visible in the band of 50°–60° latitude, but there has been a dramatic increase of sightings at lower latitudes in recent years. Do not go too far north or south because, at latitudes significantly above 60°, the sky is not sufficiently dark for much of the summer. Nevertheless, the first time I recall recognizing NLCs was in Fairbanks, Alaska (65° N) while in a canoe late one evening.

Keep in mind that the oblique illumination path and weak optical scattering restricts the vertical extent of the visible cloud, often to no higher than 10° above the horizon. You can estimate the cloud height from the angular height of the cloud upper edge at different solar depression angles.

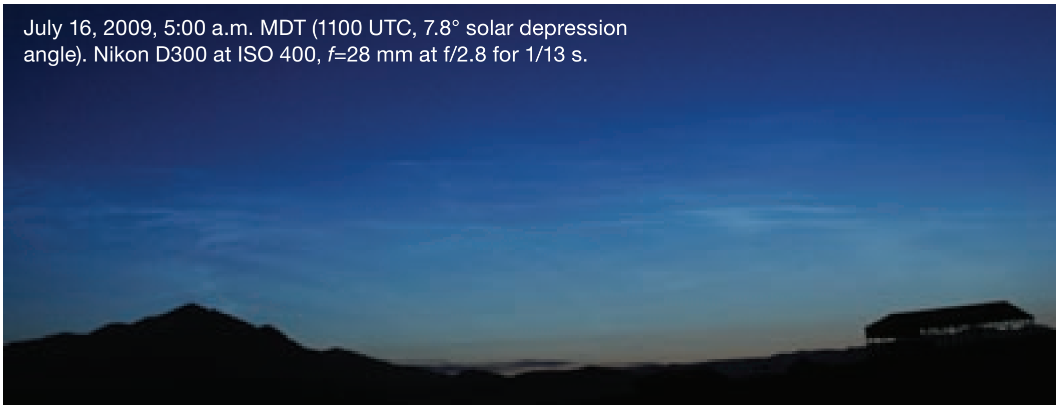
Photographing NLCs is not very difficult if you have a camera with manual exposure mode, low noise at moderately high ISO, and a firm tripod. Digital single-lens-reflex cameras are ideal because they have high sensitivity and a wide range of optically fast lenses. Furthermore, they provide the extremely valuable instant feedback required to fine-tune exposure settings. Take sufficient time to compose and expose a good photograph, but do not waste time because, especially at lower latitudes, NLCs can appear and fade quickly. However, at high latitudes the twilight develops so slowly that NLC displays can last for hours.

In determining exposure settings, remember that digital cameras do not suffer from reciprocity failure, unlike film cameras (i.e, doubling the exposure settings on the camera actually results in doubling the apparent exposure on the image). Therefore, you can use shorter exposures with a digital camera than the tens of seconds listed in books whose authors used film. In fact, my exposures are about an order of magnitude shorter than the film exposures listed in my books.

July 16, 2009, 4:36 a.m. MDT (1036 UTC, 10.9° solar depression angle). Nikon D300 at ISO 400, *f*=28 mm at f/2 for 1/3 s.



July 16, 2009, 4:50 a.m. MDT (1050 UTC, 9.1° solar depression angle). Nikon D300 at ISO 400, *f*=28 mm at f/2.8 for 1/4 s.



July 16, 2009, 5:00 a.m. MDT (1100 UTC, 7.8° solar depression angle). Nikon D300 at ISO 400, *f*=28 mm at f/2.8 for 1/13 s.

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The photographic sequence above illustrates the temporal evolution of the NLC display shown in the opening image (observed in the pre-dawn twilight in the north-northeast sky on July 16, 2009, just east of Bozeman, Mont. at 45.65° N, 111.01° W). Digital camera photographic exposure information is provided as a guide to the settings you might try. The top image is from 4:36 a.m. MDT (1036 UTC), with a 10.9° solar depression angle, 75 minutes before sunrise at 5:51 a.m. MDT. (The display became visible at 4:26 a.m. MDT when the sun was 12° below the horizon.) The middle image was recorded 14 minutes later at 4:50 a.m. MDT with the sun 9.1° below the horizon, showing some degradation of contrast as the early twilight develops. The bottom image is from 5:00 a.m. MDT, with the sun 7.8° below the horizon (14 minutes before civil twilight and 51 minutes before sunrise). The NLC contrast was fading rapidly by this time.

The thin, wispy nature and deep-twilight timing make NLCs fairly easy to identify. Nevertheless, identification of NLCs by inexperienced observers might be somewhat difficult in the presence of high cirrus clouds illuminated by moonlight or distant low clouds illuminated by light pollution.

If you live at or visit sufficiently high latitude in the summer, and you do happen on an NLC display, please consider reporting it to an observer network such as the noctilucent cloud observers' homepage, www.nlcnet.co.uk. At a minimum, I hope this article motivates you to pay attention to the sky where you live. It is filled with optical treats and phenomena for those willing to take the time to appreciate them.

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OSA Member

ONLINE EXTRA: Visit www.osa-opn.org for a slideshow and video featuring more noctilucent clouds.