Brilliant colours from a white snow cover

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Brilliant colours from a white snow cover

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Abstract
Surprisingly colourful views are possible from sparkling white snow. It is well known that similarly colourful features can exist in the sky whenever appropriate ice crystals are around. However, the transition of light reflection and refraction from ice crystals in the air to reflection and refraction from those in snow on the ground is not trivial. Photographs and videos from brilliant colourful sparkles observed in white snow covers are presented and discussed.

S Online supplementary data available from stacks.iop.org/PhysED/48/322/mmedia

Introduction

There are many different ways in which magnificent colourful light effects can be produced in Nature. Examples are rainbows caused by refraction and reflection in raindrops [1, 2], or coronas, iridescence and glories caused by scattering (diffraction) of light by much smaller cloud droplets [3–5]. Fascinating sunset and sunrise colours of the sky, Sun or Moon are caused by Rayleigh scattering from air molecules as well as light scattering from larger particles such as water droplets and aerosols [2, 6, 7]. A classification scheme of such phenomena [7] distinguishes the sort of light source (Sun or Moon), the kind of scattering process as well as the physical nature of the scattering particle itself (atom, molecule, ion, water droplet, ice crystal or aerosol). Scattering is the most general term for the interaction of light with matter; however, one usually also distinguishes reflection, refraction, interference, diffraction, etc. In the following we will omit scattering, but use reflection and refraction instead where appropriate.

Colourful phenomena from ice crystals in the air

The observable atmospheric optical phenomena associated with reflection and refraction from ice crystals within thin clouds are called halos [1, 2, 7]. Reflection halos produce colourless features, such as subsuns or the parhelic circle [1, 2], since there is no dispersive effect involved in the reflection (such as the wavelength separation that occurs with refraction of light in a prism or diffraction of light from a grating). On the other hand, refraction halos produce coloured features, such as the parhelion or sun dog, through wavelength-dependent bending of light rays in the ice crystals. A large number of different halo types are now known, depending on ice crystal geometry and orientation as well light paths through the crystals [8].

Some of the most vivid and colourful halos are parhelia (figure 1), also commonly called sun dogs. These are caused by refraction in hexagonal

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Figure 1. Example of a parhelion located 22° to the right of the Sun. This halo portion was photographed 2 September 2008, at Bozeman, Montana, USA at 7:14 pm (Sun elevation = 7.1°). Photographed with a Nikon D300 camera and Nikon 18–200 mm lens at $f/16$, 1/800 s, ISO 250.

ice crystals that have typical dimensions of 10–100 μm [1, 2, 7, 8].

Light from the Sun (or Moon) enters a side face of such a crystal. The light is refracted and may exit via a second refraction process through a second side face, as depicted in figure 2(a). Overall, the two refractions combined can also be considered as refraction by a 60° prism. The results are well known in physics teaching: the incident white sunlight is spread into a colourful spectrum and the effect is most pronounced if the refracted light within the crystal is parallel to the base of the prism. This reflects the minimum deviation condition for a prism. For ice crystals with an index of refraction of approximately 1.31, the minimum deviation corresponds to a refraction angle of about 22°. If there are many such crystals in a cloud with all possible orientations, an observer will see a circular halo forming a ring around the Sun with angular radius of 22°. If instead the crystals are oriented with their symmetry axis pointing in the vertical direction, the observable feature can only be seen on both sides of the Sun (figure 2(b)), which results in the so-called sun dogs (figure 1).

Which condition actually occurs in a cloud—random or vertical orientations of the symmetry axis—depends on the kind of hexagonal crystal (thin plates or column crystals) and meteorological conditions within the cloud (laminar or turbulent flows).

The more obvious question, however, is, when will such hexagonal ice crystals with near optical quality surfaces—the prerequisite for halo observations—be present in atmospheric clouds below freezing temperature? One does not observe halos every day, hence there must be special conditions for these crystals to exist. Indeed, hexagonal prisms (plates or columns) can only grow in clouds for well-defined combinations of water vapour supersaturation and temperature. The transport of water molecules within the cloud from water droplets towards ice crystals is driven by different saturation vapour pressures of ice versus the supercooled water droplets. The hexagonal plate or column crystals must compete with other kinds of ice crystals, such as snowflakes with dendritic (needle- or tree-like) geometry, which usually grow in a

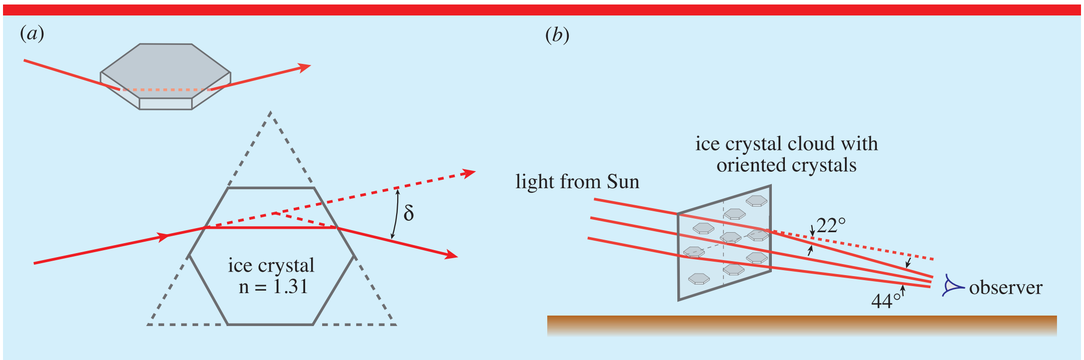

Figure 2. Refraction of light from hexagonal plate ice crystals leads to a pronounced feature at an angle $\delta = 22°$ (a). If many crystals are all oriented with their symmetry axis vertical (b), light is scattered sideways and gives rise to parhelia, also called sun dogs.

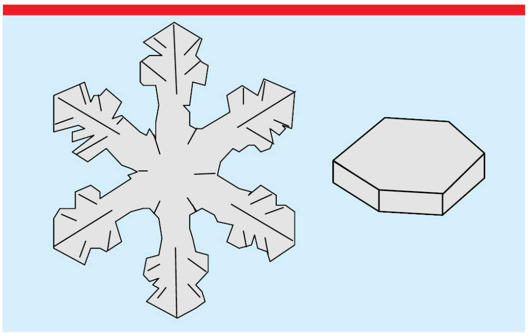

Figure 3. Two of the multitude of possible snow crystal shapes. Depending on supersaturation and temperature, simple hexagonal plate crystals may form (right), but in the majority of cases complex crystals are formed, which retain six-fold symmetry, but of a dendritic (tree-branch-like) geometry (left).

much wider range of conditions (e.g. [9, 10]). This explains why halos cannot be seen in every thin cloud. In the scientific literature the criteria for creation of crystals with various possible geometrical shapes are discussed in the context of snow crystal morphology. The crystal growth mechanisms are quite complex and are well beyond the scope of this paper. They involve particle diffusion, heat diffusion, surface attachment kinetics, growth instabilities and the role of different impurities on crystal growth [10]. As an example, figure 3 depicts just two of the many possible geometric forms of snow crystals. Excellent photographs of natural and artificially grown snow crystals are available; see, for example, the particularly nice popular science book by Libbrecht and Rasmussen [11].

The white colour of snow

Before turning to the colours that are observable in snow layers, we must briefly discuss the absorption and reflection/refraction of light in snow crystals and answer two questions. First, why do individual snowflakes look white, and second, why do we usually see white colour when looking either into a snowstorm or onto a cover of snow on the ground? Like the colour of most objects, the colour of snow is a result of absorption and reflection/refraction of light. The absorption properties of small ice crystals are well understood and only a short summary will be given (for details, see [12]). In brief, the absorption coefficient of ice is quite small, such that light must travel a long distance of several metres to be attenuated appreciably. The attenuation for blue light is less than that for red, which is why light transmitted through thick layers of ice appears blue. In contrast, light reflection/refraction by optically large ice crystals is more or less independent of wavelength since usually snow crystals do not have near optical quality surfaces; i.e., any intrinsic colour of ice crystals (and, hence, also snowflakes) needs to come from absorption. Individual snowflakes are so small that transmitted light is not attenuated appreciably. Any individual snowflake or snow crystal, therefore, cannot usually gain any colour in either absorption or reflection/refraction (colours can only arise in the above-mentioned refraction process for optical quality surfaces if present).

Looking into a snowstorm or looking towards a snow-covered surface resembles more or less similar physics problems to looking into clouds or fog. The main difference between snow cover and clouds or a snowstorm is that individual crystals are much more densely packed in snow on the ground.

Common to all of these problems is that the respective particles (droplets, snowflakes or, in general, snow crystals of irregular geometry) are usually large compared to the wavelength of light. Therefore, forward scattering is dominant, which means that any individual scattering event will only lead to a slight change of angle with respect to the incident light. This means that light that is scattered towards an observer from arbitrary angles needs to undergo many individual reflection/refraction events; in other words, multiple scattering is needed.

Let us now discuss the colour of snow on the ground. Snow cover of only a few cm is sufficient to produce a colourless, white appearance; therefore, it is obvious that the total path of the scattered light is of a similar order. The absorption in ice particles with such distances is negligible and cannot produce colour. In addition, reflection/refraction from such optically large crystals is more or less independent of wavelength, which means that snow on the ground should look white, indeed. Furthermore, because of multiple scattering, distinct optical effects are

Figure 4. The glitter path of an ice layer that has formed on a snow cover recorded at 4:24 pm 22 January 2011 (Sun elevation = 14.5°) near Bozeman, Montana USA. Photographed with a Nikon D300 camera and Nikon 18–200 mm lens at $f/16$, $1/1000$ s, ISO 320.

Figure 5. A snow-covered area with many white glints and colourful sparkles. Photograph recorded with a Canon EOS 1000D camera (Canon 18–55 mm lens) 4 February 2012 in Brandenburg, Germany at 3:33 pm, corresponding to a Sun elevation of about 10.1°.

observable from only the top layer of snow on the ground instead of from underlying layers.

In ‘Observations of brilliant colourful spots from snow and ice crystals on the ground’, however, we demonstrate that it is nevertheless possible to observe brilliant colourful sparkles from a white snow cover. The obvious question that follows from the above arguments is, how can this be possible?

Colourless natural phenomena from snow and ice crystals on the ground

The top of a snow layer usually contains a huge variety of different crystals and also different crystal orientations; therefore, it is not surprising that sunlight directed towards a snow surface will—in addition to some sideways scattering—be partially reflected in the specular direction. If part of the surface has previously melted and subsequently frozen again, larger areas act as mirrors to produce glitter paths (figure 4) similar to those from a slightly disturbed sea surface at low Sun [2, 13, 14], where reflections originate from the water surfaces due to tiny wind waves which are accidentally oriented to reflect incident light towards the eye of an observer.

At first sight, ‘glitter path’ reflections from snow without ice cover are less impressive since they consist only of isolated individual sparks; however, under appropriate conditions, there may also be thousands of sufficiently clean surface areas of tiny individual ice crystals on the top layer of snow that happen to have the proper orientation. Even with slight motion, an observer will perceive a constant change of individual white sparks entering the eye, which alone is already a spectacular and fascinating sight [15]. It was, in fact, a desire to observe such white spark effects that led to our observations of brilliant sparkles of colourful light on fresh snow.

Observations of brilliant colourful spots from snow and ice crystals on the ground

Figure 5 depicts a snow-covered area with some footprints illuminated by a low Sun. While walking along, one could readily see bright sparkling spots of light, both white and coloured, which can also be seen on the photograph if observed closely. This photograph nicely illustrates what a snow cover should look like at first glance when searching for sparkles.

The two photographs in figure 6 depict enlarged views of the ground, revealing a typical feature of the sparkles. Since the Sun only has an angular diameter of around 0.5°, its radiation arrives with nearly parallel rays, which means that refracted monochromatic light bundles exiting the crystals are also about parallel, corresponding to a focus at infinity. Hence, if the image is focused on the surface of the snow at a distance of a few metres, the coloured sparkles will be small and not very impressive looking (figure 6(a), left). However, if the image is focused near infinity, the colourful spots appear as brilliant circles on top of the white snow (figure 6(b), middle). Of course, contrast enhancement may be applied later on using image processing to make the effects better

Figure 6. The same area of snow with a width of about 1 m (see the edge of the footprint at the left side) focused on the snow surface (a) and focused at near infinity (b), as well as a respective contrast-enhanced image (c). Photographs were recorded with a Canon EOS 1000D camera (Sigma 70–300 mm lens) in Brandenburg, Germany 4 February 2012 at 3:34 pm, corresponding to a Sun elevation of about 10.1°.

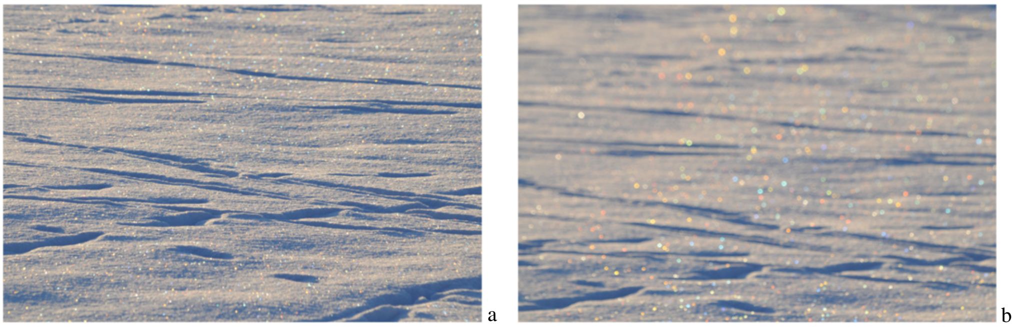

Figure 7. A snow-covered area showing colourful sparkles with the camera focused close to the ground (a) and focused close to infinity (b). Photographs were recorded at 5:12 pm 28 November 2009 near Bozeman, Montana, USA (Sun elevation = 3.9°). Camera: Nikon D300, Nikon 80–400 mm lens, $f/11$, $1/500$ s, ISO 500.

visible—we only show one example (figure 6(c), right).

Figure 7 shows another example. In figure 7(a) (left) the front part of the ground is in focus, whereas in figure 7(b) the focus is close to infinity. Obviously, the sparkles are now much easier to spot all across the field of view.

As a matter of fact, such coloured sparkles are well known. Lynch [2] calls the colourless glitter-like specular reflections from individual snow crystals ‘glints’ and the colourful ones ‘sparkles’, and we will adopt these names in the following. Although well known, these sparkles are probably not often observed consciously or even intentionally. Therefore we want to explain the phenomenon in more detail and also give hints on when and where to look for them next winter.

First, our eyes usually do not focus on the ground, but rather on more distant objects. If looking at the snow cover in the proper direction, i.e. more or less in the direction of the Sun, it is usually easy to see the sparkles if the meteorological conditions are appropriate.

When searching for sparkles on the ground, it is easiest to note the transient phenomenon while moving, since the human eye easily catches changes within the field of view. This is illustrated with two movie sequences in real time, which are included as supplementary material (available at stacks.iop.org/PhysED/48/322/mmedia; they are best viewed using VLC player or a similar package that allows observation at a reduced frame rate). Movie 1 was recorded at low Sun in the afternoon (around 4 pm, 11 February 2012). To reduce the brightness of the strong light reflection from the snow the phenomenon was observed through sunglasses (this also reduced the saturation effects of the camera sensor). Figure 8 shows a snapshot of the daylight video, automatically focused more or less on the snow surface. The coloured spots can be noticed easily against the snow background. In the middle of the video, the sunglasses were removed and the

Figure 8. Snapshot from an HD video (Casio Exilim FH100) observed through sun glasses. The glasses reduced the radiation level such that the sparkling spots could be seen more easily. The Sun elevation was 9.1°.

camera sensor had to readjust to the brighter signal.

Analysis of the video with suitable software (e.g. Windows Movie Maker or similar) allows comparison of one frame with the next. Doing this allows one to study what happens to individual spots while moving. First, it is possible to see colour changes of individual spots while moving. Second, one can observe individual spots develop into bright sparkles, change colour, but then, after moving only a few degrees, decrease again in brightness until they disappear. Obviously, there is an optimum light scattering angle near 22° defined by the Sun and the crystal, and if the observer's eye looks in just the right direction, it sees a sparkle. Moving on, it misses the scattering angle from that ice crystal, but may see one from another.

One can also carry out similar experiments at night; for example, observing a snow-covered lawn illuminated by a street light or any other white light source. Movie 2 (available at stacks.iop.org/PhysED/48/322/mmedia) shows such a night scene where the lantern had an incandescent light source. The glittering sparkles reward the observer well for the freezing cold outside air. We note that street lights are usually close by objects. However, for typical light bulbs of 5 cm diameter, a distance of 10 m is already sufficient for the light to be mostly parallel. An ice crystal on the ground would see such a light source as having an angular diameter of only 1.4°, which is only slightly larger than the 0.5° of the Sun.

Explanation of the phenomenon

The colourful sparkles from snow covers arise from refraction of sunlight by individual hexagonal ice crystals in the top layer of snow on the ground in essentially the same way that parhelia (sun dogs) arise from refraction of sunlight by ice crystals suspended in the air (see figure 1). The observed angle in both cases is around 22°. Whereas halos can be observed at any time of the year in the sky if clouds with appropriate ice crystals are present, sparkles can be observed only for short periods after snow falls, while the appropriate meteorological conditions persist. These statements are supported by the following arguments.

(1) *Sparkles occur at about the same angular positions as 22° halos and parhelia.* Figure 9(a) depicts a photograph of a winter landscape, showing a nice parhelion in the sky. Extending an imaginary 22° ring across the photo onto the snow cover, one immediately realizes that where it is located on the snow there is quite a bit of glitter. Figure 9(b) shows an enlarged portion of the snow cover, which nicely reveals the colourful sparkles arising from a 'snow-surface parhelion'. This coincidence of angles strongly suggests that the same type of crystal, here hexagonal plates, is responsible for the parhelia in the sky and simultaneously for the sparkles on the snow cover.

(2) *Plate crystals were indeed in the top layer of snow on the ground when sparkles could be observed.* To make sure that the snow cover did indeed include hexagonal crystals, strongly magnified sections of the snow were investigated for the observations of figures 5, 6 and 8, using a close-up lens. Figure 10 shows part of one such photograph (a) and an enlarged section (b), which clearly exhibits some hexagonal plate crystals within the top layer.

Now, since it is proven that hexagonal crystals exist in the top layer, it is easy to imagine how the sparkles are produced. Similarly to figure 2, figure 11 schematically shows how an ice crystal can scatter sunlight via two refractions. Owing to the dispersion of the ice, the colours of the incident light

Figure 9. Simultaneous observation of parhelia in the sky and colourful sparkles on the snow-covered ground at 3:46 pm on 1 January 2011, near Bozeman, Montana, USA (Sun elevation of 14.6°). (a) Full view and (b) enlarged portion of the foreground showing colourful sparkles at the parhelion angle. Camera: Leica C-Lux 3, 22 mm, $f/6.3$, ISO 100.

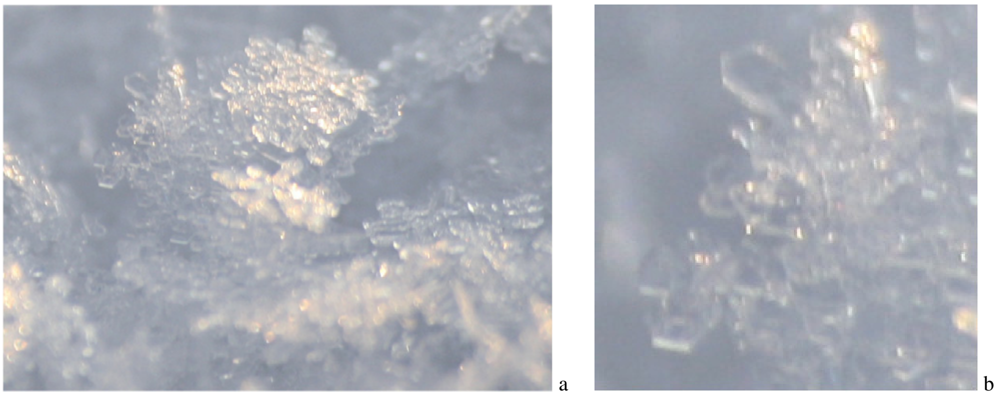

Figure 10. The snow surface in Brandenburg, Germany at the same time as figures 5, 6 and 8, photographed with a close-up lens (a), and an enlarged portion of the upper-left corner, clearly showing hexagonal structures (b). Recorded with a Canon EOS 1000D camera and Sigma 70–300 mm lens.

are spatially separated. The minimum deviation angles for such 60° prisms are 21.7° for red and 22.5° for blue light (e.g. [2]). Imagine an observer walking in the snow. When looking at an angle, the distance to the snow surface is probably at least 2 m, hence the red and blue light will have already spread by about 3 cm, which means that an observer will only see one colour at a time from any individual crystal.

While walking or moving his or her head, the observer's eye position constantly changes with respect to an individual ice crystal. Therefore, one may briefly observe a different colour sparkle from the same ice crystal. In addition, a change of the orientation gives rise to many more different ice crystals that now fulfil the condition for being observed. As a consequence—while walking—there is an ever-changing

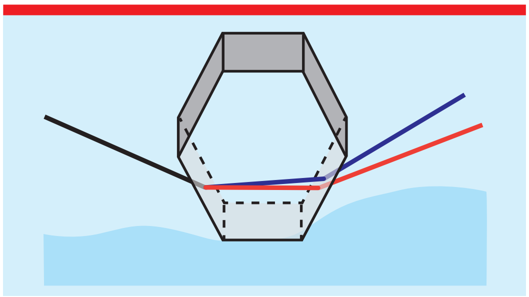

Figure 11. An enlarged schematic view of a hexagonal symmetry ice crystal on the ground, which gives rise to colourful refraction effects. If oriented properly, the refracted light may enter the eye of an observer, producing the sensation of a brilliant colourful sparkle.

perception of glittering colourful sparkles. Stereoscopic vision is not important; that is, the sparkles can also be seen by one eye alone or by a camera.

(3) *Empirical data on frequency of observation*. Although well known, the phenomenon is not always observable when the Sun is illuminating a snow-covered surface. The observations at Brandenburg, Germany (figures 5, 6, 8 and 9) were made at the beginning of February 2012. After a mild January, winter struck hard and temperatures were well below freezing. In the period under discussion, nighttime temperatures went as low as −20 °C for a period of about two weeks. Clouds brought snowfall two to three times, typically less than 5 cm each time, and every now and then there were wonderful clear blue skies and sunshine during the day. The phenomenon was typically observable for one, or at most two, consecutive days after fresh snowfall.

Similar observations were made in Montana, USA. One of the authors—being a passionate nature photographer—has a huge collection of photographs of natural phenomena with more or less continuous coverage of all winters in Bozeman, Montana since 2001. Checking of all winter and snow scenes within this period also revealed that the sparkle phenomenon could only be observed a couple of times each winter, usually the day after new snowfall.

This is also consistent with observations of glints (white glittering spots), where it was stated [15] that the effect was most brilliant for fresh dry snow and a clear day and that the sparkles (as they were called in [15]) lost their brilliance after the snow melted slightly.

(4) *Transient morphology changes within snow covers*. Snow on the ground differs significantly from snow crystals in the atmosphere (see, e.g., [16–18]). In terms of crystal growth theories, snow is usually a polycrystalline aggregate, initially very loosely packed, but changing over time. Simultaneously, the geometrical shape and size of the individual snow grains may also change. The metamorphism of snow can be characterized by three idealized categories [16], and in Nature one will usually find a mixture of these.

The first category is unmetamorphosed snow, where one assumes that the snow cover grows by deposition of snow crystals from the atmosphere. Without wind, one may assume that the deposited snow crystals more or less resemble those in the air, whereas additional wind may break down the delicate structures of the crystals and thus change them upon deposition.

The other two idealized categories describe the two most important metamorphic processes that take place in below-freezing snow covers. The second category refers to equi-temperature and the third to temperature-gradient metamorphism. Under equi-temperature conditions, one assumes equal temperature throughout the snow cover. In this case, water molecules move largely via vapour diffusion to decrease the surface free energy, the latter being proportional to the surface area. This mechanism will continuously decrease the surface energy by strongly reducing the curvature of sharp points, such as dendritic needle-like structures. The rate at which this process proceeds depends on the temperature, being very slow for low temperatures.

For temperature-gradient metamorphism (typical gradient between 10 and 100 $\mathrm{K\,m^{-1}}$), one assumes an idealized linear temperature gradient within the snow cover. The gradient provides the driving force for processes that tend to decrease the gradient. In particular, the gradient drives water vapour transport from warmer temperatures to colder ones. New dry snow covers are usually warmer at the bottom [17], resulting in heat flowing from the bottom to the top. In stacked layers of snow crystals, the grains will sublime at the warmer tops of the layers while simultaneously growing at the colder bottoms of the layers above. This leads to pyramid-shaped grains within the layers.

Obviously, the actual combination of all these processes depends on the meteorological conditions. One may start, for example, with a fresh, dry snow cover and little wind, which means that hexagonal plates or columns—if present in the air—will also be deposited on the snow cover and may produce observable sparkles. For low temperatures, equi-temperature metamorphism will proceed slowly. If the air temperature drops during a clear sky night, temperature-gradient metamorphism may start, which will change the grain sizes and geometries, while developing pyramid-like structures. This may destroy individual plate or column crystals. If, instead, the temperature rises above the freezing point, crystals will start to melt, which also rapidly reduces the number of crystals.

Overall, these mechanisms easily explain why metamorphism processes—irrespective of kind—change the crystal geometries within the top layer. Therefore, it is plausible to assume that meteorological changes like temperature drops during the night or warming during the day can easily prevent any observations of colourful sparkles from the snow surface. In this case, one has to wait for the next snowfall to deposit new crystals on top.

Summary and conclusions

Colourful sparkles were observed from fresh snow cover, arising from refraction of sunlight by individual hexagonal ice crystals within the top layer of snow. It has been shown that hexagonal crystals are responsible for the phenomenon occurring at observation angles of around 22° with respect to the Sun. We have discussed how ice crystal morphology changes driven by meteorological changes can easily alter crystal geometries, thereby destroying the conditions required for observing sparkles. This phenomenon—although relatively rare—is fascinating. Similarly to other atmospheric optical phenomena, it will be seen more often when being searched for, while knowing when and where to look. It may easily serve as a nice physics project for students in winter time.

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