A Field Guide to Lens Aberrations

Sourangsu Banerji
Senior Optical Engineer
Momentum Optics, LLC.

In this article we will review one of the most common problems that affects the design of our camera lenses: aberrations.

Through this article we hope to give you practical knowledge about the common technical problems of lens design and how they actually affect our photos. Most of all, this article is here to help understand one aspect of why one lens will produce a better, more accurate photo than another. It is an especially nice bit of knowledge and skill to possess when choosing equipment for use in even basic photography.

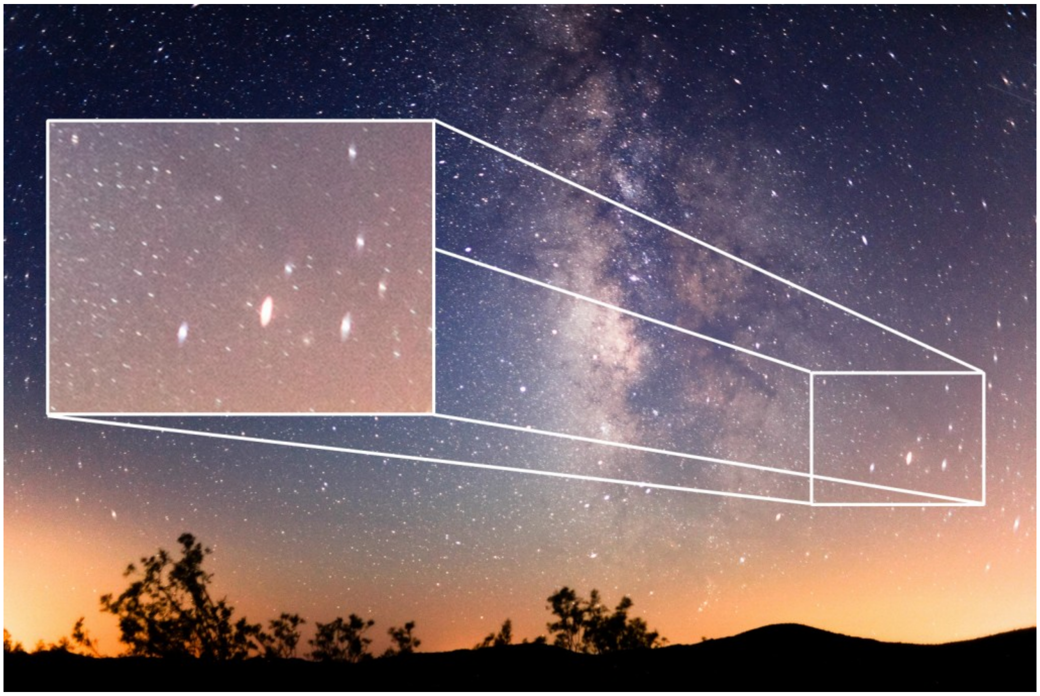
What is an aberration?

An aberration is simply an imperfection in the way a lens focuses light. There are a number of different classifications of aberrations, and they affect things like the sharpness, color, focus, magnification, and distortion in your photographs.

From the lens designer's perspective, aberrations are the primary challenge when designing a lens. It is almost entirely the presence of aberrations that limits a lens's performance from a standpoint of accurate image reproduction. Ideally, a lens designer wants a white pinpoint of light to always look like a white pinpoint of light, regardless of its position in the frame. But that's not always how it turns out, especially when using fast wide angle lenses, like the lenses I recommend most for shooting landscape astrophotography.

In astrophotography, our subject tends to be point sources of light (stars) against a highly-contrasting dark background (space) so the presence of lens aberrations can appear to be *more prevalent* in astrophotos than in other types of photography.

A lens with a prominent aberration will drastically distort the shape of the stars, especially towards the outer edges of the frame. One of the first lenses that I used for making astrophotos, the Canon EF 28mm f/1.8 USM (Amazon / B&H), has especially bad aberrations when used at its lowest f/number, and the problem is very apparent in its photos of the stars. In the sample photo of the Milky Way below, you can see how the stars in the corners of the image are stretched and distorted, the result of the lens aberrations present in Canon EF 28mm f/1.8 USM.



Canon EF 28mm f/1.8 USM Aberrations

Chromatic aberration and monochromatic aberration are the two main types of aberration.

Chromatic aberrations are imperfections in the way a lens disperses different colors of light, much like the way a prism splits light into a rainbow. Monochromatic aberrations are problems in the way a lens focuses a single color of light.

Nearly every lens I have ever used shows some degree of chromatic and monochromatic aberration when being used for astrophotography, especially when the lens is used wide open, at its lowest f/number setting. Typically, aberrations are more prevalent on lenses with low f/numbers. In most cases, the aberration can be reduced by stopping the lens to a higher f/number. This is most inconvenient for astrophotography because lower f/numbers tend to be more desirable for collecting more light from the faint stars. Choosing a lens or setting an f/number for an astrophoto is often a balancing act between collecting ample light for the exposure with a low f/number and reducing the effect of aberration with a higher f/number.

Lens Design

For most forms of photography, aberrations will tend to soften the image, particularly in the corners of the frame. The sharpest lenses tend to have low levels of aberration. Lens manufacturers usually go to great lengths to design a lens that has as few visible aberrations as possible, usually through the addition of corrective lens elements to their design.

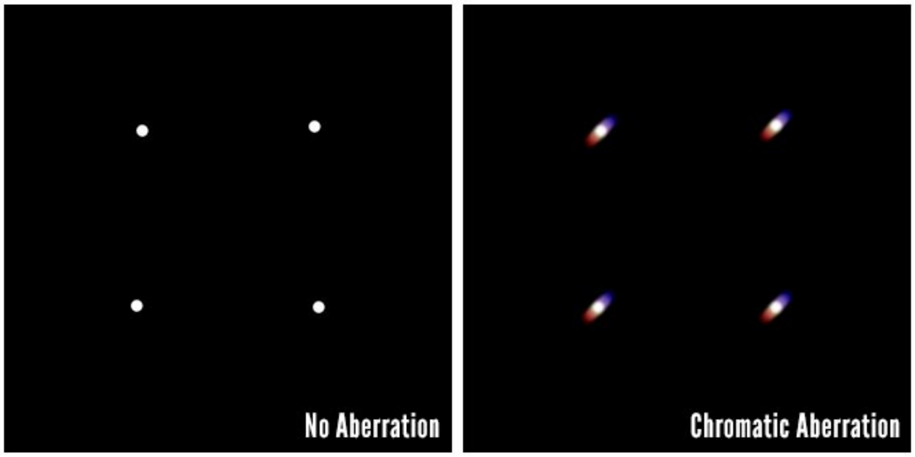
The lens designer will usually add specially shaped elements to target a specific aberration. Sometimes, making one correction can introduce another aberration, so lens designs can become exceedingly complex when designers keep adding corrective elements to try to curb the presence of aberrations introduced by others.

The Zeiss Otus 55mm f/1.4 lens has 12 elements in 10 groups (via zeiss.com)

A perfect example of a well-corrected lens is the monstrous Zeiss Otus 55mm f/1.4 (Amazon / B&H). It's arguably one of the sharpest full frame lenses ever made (dpreview.com) and as a result of its complex lens design, it's also one of the largest standard primes ever made for a full frame DSLR. So, when Zeiss brags about having 12 elements in 10 groups in the 55mm Otus, they are talking about how many additional corrective lenses were added to achieve the improved performance. Compare that number to the much cheaper Canon 50mm f/1.8 STM (Amazon / B&H) lens, with only 6 elements in 5 groups, and we can see that it took twice as many pieces of glass for Zeiss to produce their better design. Now more lens elements don't specifically mean that a lens will be better, but it does give us some indication as to how hard a lens designer tried to curb aberrations.

Now let us review the two main types of aberrations, what some of them look like for point light sources (like stars), and some real world examples of each.

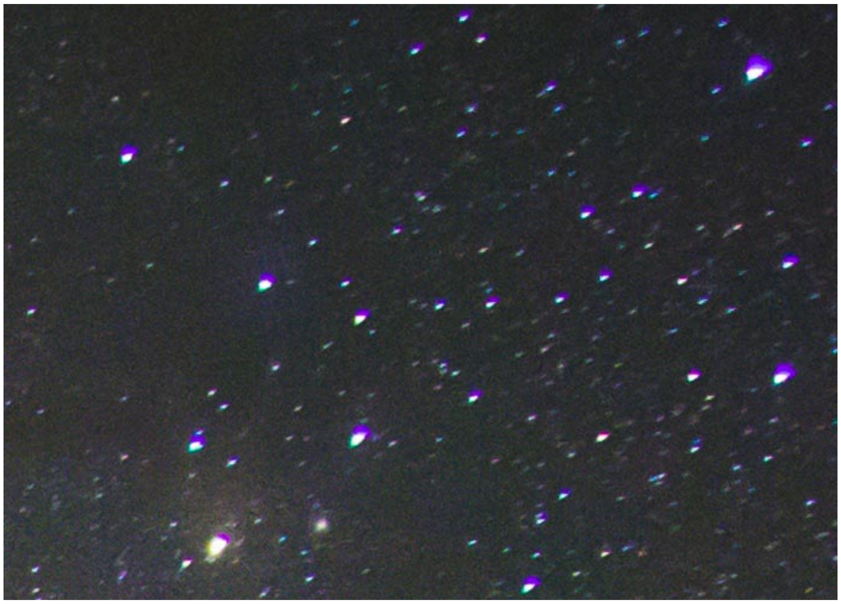
1. Chromatic Aberration



Chromatic aberration is a dispersion problem that causes white light to split into its respective colors of the rainbow.

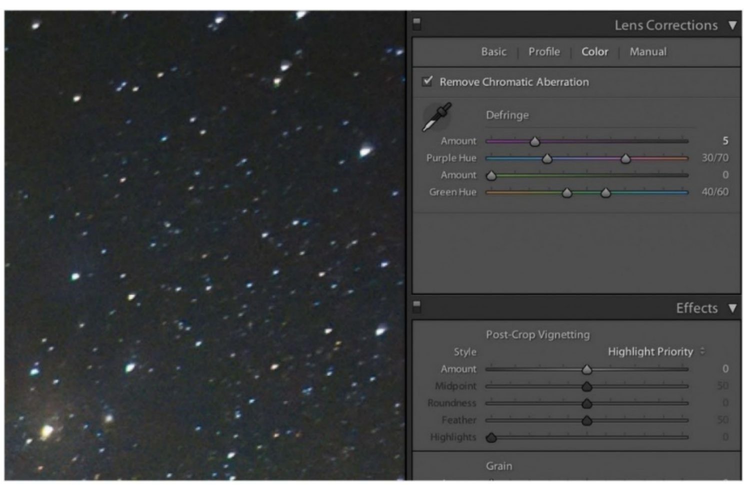
Most lenses are fairly well corrected for chromatic aberration, but it is not uncommon, especially with fast lenses, to still see small signs of chromatic aberration, especially in the corners of the image, particularly when photographing very high contrast objects like tree branches against a bright white sky.

Milky Way Galactic Center shot with the Rokinon 12mm f/2 NCS CS



While the Rokinon 12mm f/2 is a relatively low aberration lens, it still has some visible chromatic aberration.

In astrophotography, chromatic aberration often shows up as a colored edge on one side of a star. Lens manufacturers often use a combination of different shaped low and high dispersion lens elements to correct for chromatic aberrations. That said, it is still common for many modern lenses to show purple or green fringed highlights in high contrast areas of the image. In the image above from my Rokinon 12mm f/2 review, you can see very distinct purple edges around one side of all the overexposed highlights and a small amount of green on the opposite side of the highlights — a perfect example of lateral chromatic aberration.



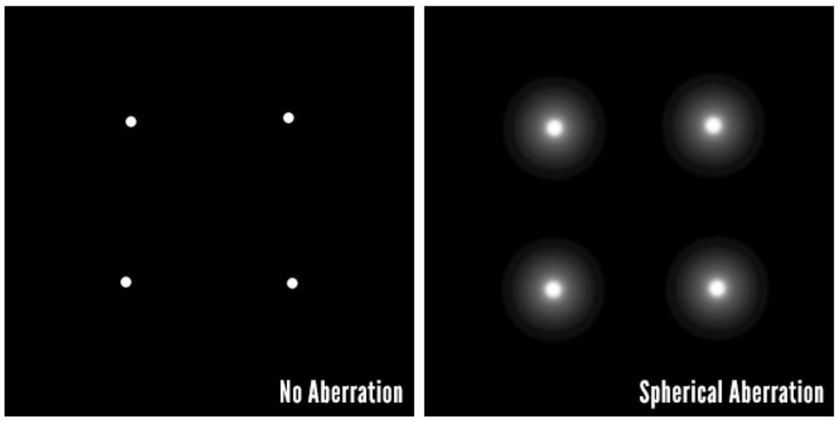
Adobe Lightroom's chromatic aberration correction tools in the Lens Corrections Color Tab

I personally do not spend a lot of time trying to correct for chromatic aberration in post processing, as it is usually not detrimental to a photo as a whole. In cases where it is distracting, Adobe Lightroom and Adobe Camera Raw both have useful and easy to use chromatic aberration correction tools.

2. Monochromatic Aberrations

All of the following aberration types are forms of monochromatic aberration. Again, monochromatic aberrations are problems in the way a lens focuses a single color of light.

Spherical Aberration



Spherical aberration will cause point sources of light to show soft, symmetric halos.

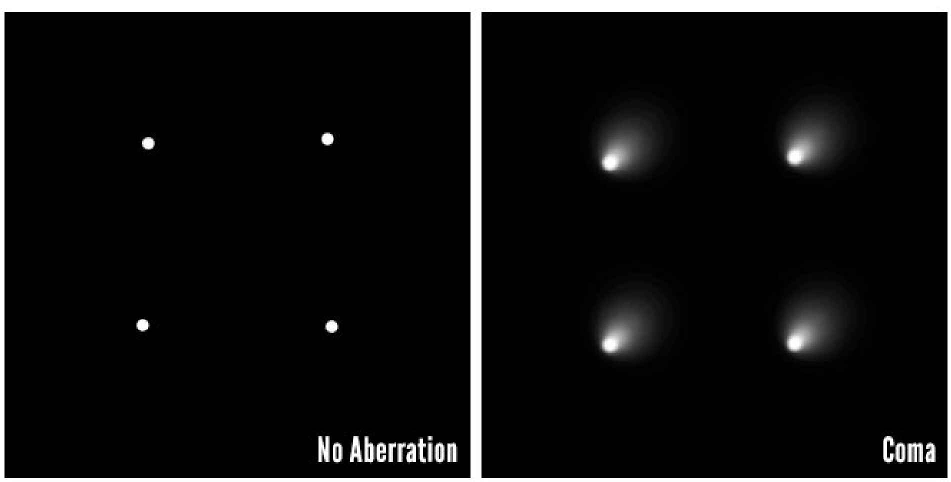
It is a problem created by the use of spherically-shaped lens elements that have different focal lengths at different aperture diameters. Light rays traveling through the edge of the lens aperture are focused on a different distance than light rays traveling through the center of the lens aperture. While it will still allow a lens to create a sharp round pinpoint star, spherical aberration tends to lower the overall contrast of the image across the frame. Unlike most of the other aberrations that are most visible towards the edges of the image, spherical aberration will still be noticeable on central portions of the image.

The Milky Way shot on the Rokinon 24mm f/1.4

The Rokinon 24mm f/1.4 shows a small amount of spherical aberration at f/1.4

Most lenses are fairly well-corrected for spherical aberration, especially from the common use of aspherical lens elements to help correct for spherical aberration. One case where I have encountered a small amount of spherical aberration is actually on my favorite lens for astrophotography: the Rokinon 24mm f/1.4 (full review), despite its use of aspherical elements. Wide open at f/1.4, the lens shows distinct halos around bright stars in the center of the image. The halos go away when stopping down to about f/1.7 to f/2.0. Overall, a small amount of spherical aberration is not as visually detrimental to an astrophoto as some of the other aberrations, because stars tend to still appear round and the added “hazy” look actually accentuates star colors, similar to the look you would get if you were using a fog filter.

Comatic Aberration



Comatic aberration or just “Coma” is named for its comet like shape for point light sources.

Coma occurs when light from a single source entering at the edge of the lens is not projected at the same size as light entering the center of the lens. For this reason, it becomes more apparent on point sources of light at the edge of the frame and at low f/numbers. Coma is common on fast (large aperture or low f/number) lenses but can also be reduced by stopping the lens to a higher f/number. A lot of lens aberrations that distort the shape of light sources like stars are often assumed to be coma, but sometimes the explanation is more complex. The easiest way to recognize pure coma is by its comet-like shape.

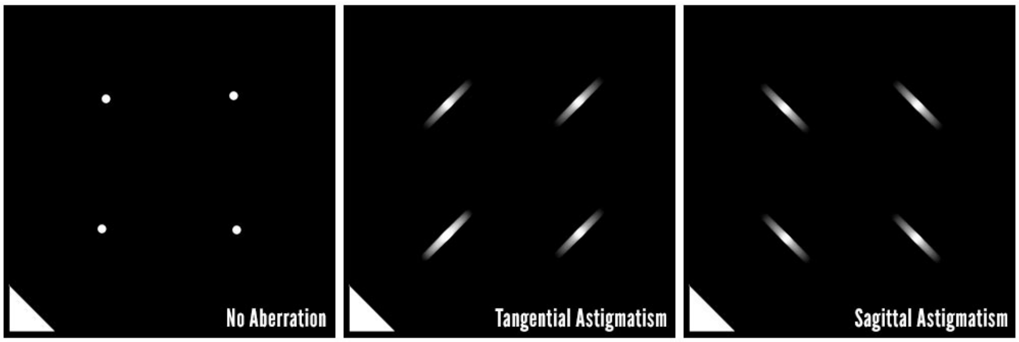
The Milky Way Galactic Center shot on the Voigtländer 50mm f/1.1 Nokton at f/1.1

The Voigtländer 50mm f/1.1 Nokton shows a heavy amount of internal coma at f/1.1

Coma can occur in either of two directions. When the tails point away from the center of the image, it is called "external coma" and the opposite is "internal coma." The Voigtländer 50mm f/1.1 Nokton

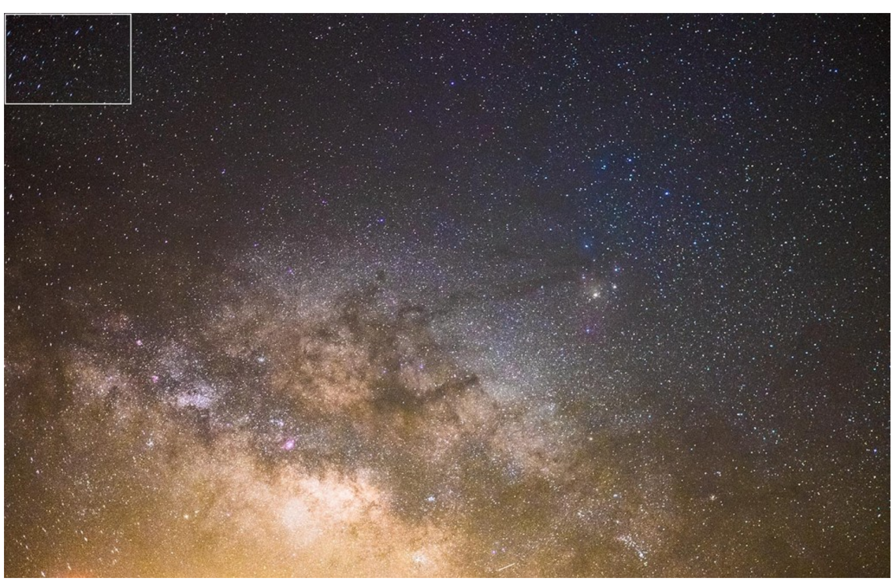
(Amazon / B&H) is an example of where a lens manufacturer decided that speed was more important than correcting for aberrations. The shows heavy internal coma in the mid field of its frame. It transitions into a combination of internal coma and sagittal astigmatism by the edge of the frame. Most of the severe aberrations on the 50mm f/1.1 Nokton are reduced once stopped to at least f/2.8.

Tangential and Sagittal Astigmatism



Astigmatism causes point light sources at the edge of the frame to appear to stretch in a line.

Astigmatism can occur in two directions depending on the direction that the light is spread, relative to the optical axis that runs along the center of the lens. In the graphics above, the white triangle on the bottom of each frame indicates the direction towards the center of the image. Tangential astigmatism spreads point light sources in lines that seem to radiate from the center of the image while sagittal astigmatism spreads the point light sources as if rotated about the center of the image. Astigmatism is apparently one of the most difficult aberrations for lens designers to fully correct.



The Milky Way Galactic Center shot with the Fujinon 23mm f/1.4

Fujinon 23mm f/1.4 R sagittal astigmatism in the extreme corners of the image at f/1.4

In my experience, astigmatism is certainly one of the most common aberrations that I see, even in expensive lenses. The Fujifilm 23mm f/1.4R (Amazon / B&H) , while a very nice lens otherwise, shows a noticeable amount of sagittal astigmatism in the extreme corners at f/1.4. The astigmatism goes away when stopped to f/2.0.

Distortion

Distortion is caused when the lens projects different sized images at different points along the frame.

This can happen in either direction, where the image at the edge of the frame appears smaller than the image at the center (negative or barrel distortion) or where the image at the edge of the frame appears larger than the image at the center (positive, rectilinear or pincushion distortion). A fisheye lens is a perfect example of a lens with extreme levels of negative distortion.

Rokinon 8mm f/2.8 Fisheye II, Fujifilm X-T1, Valley of Fire State Park, Nevada

Distortion can be particularly noticeable when photographing things, you would expect to be straight. An extreme example of this is the photo above made with a Rokinon 8mm f/2.8 II (Amazon / B&H) fisheye lens. By pointing the camera upward, the lens severely distorted the horizon and the road on which I was standing.

Some lenses can show a combination of both positive and negative distortion called moustache distortion due to the wavy nature of the way it distorts straight lines. The Rokinon 14mm f/2.8 (full review) is a lens that exhibits pronounced moustache distortion.

In terms of practical effects on astrophotos, distortion doesn't tend to be a huge problem, but in the case of lenses like that Rokinon 14mm f/2.8 that have distracting distortion, the effect can usually be corrected in post processing in Adobe Lightroom or Adobe Camera Raw with a lens profile (Adobe Lens Profile Downloader). For fisheye lenses, I tend to like "undistorting" them with a "defishing" method.

Field Curvature

Field curvature is when the lens does not focus the light onto a perfectly flat plane and instead focuses on an imaginary curved surface.

Since the sensor of most cameras is flat, this will cause changes in focus across the image. Field Curvature will usually appear as if the edges of the frame are out of focus while the center is in focus and vice-versa. Field curvature is actually a trait that has been used to artistic effect in novelty lenses like the Lomography Petzval Lens (B&H) which is known to produce "swirly bokeh" due to its combination of pronounced vignetting and field curvature. I have found field curvature to be most prevalent on older lens designs. It usually does not occur on more modern lenses.

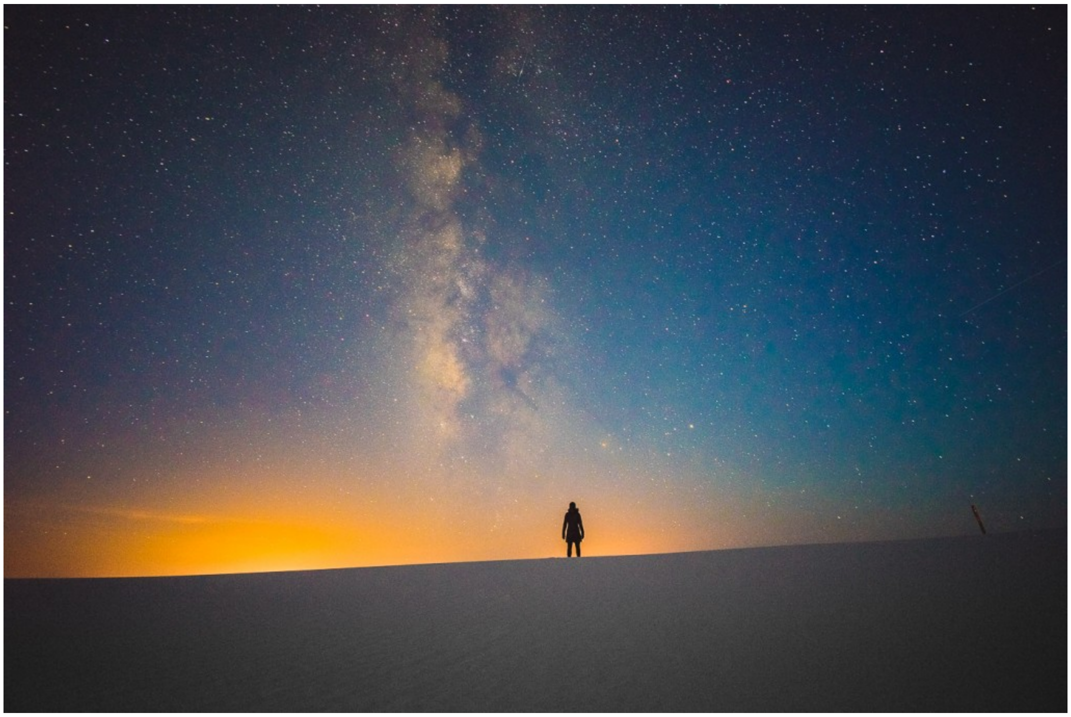
Semi-swirly bokeh due to field curvature. Voigtländer 40mm f/1.4 Nokton S.C.

I haven't personally used the modern Petzval Lens but my 40mm Voigtländer (Amazon / B&H) does have a little bit of field curvature that can be seen in the portrait of Diana above. The background lights in the center of the image are more out of focus than the lights at the edges of the image, a good indicator of field curvature.

3. Other Lens Imperfections

Vignetting

Vignetting causes the edges of the frame to appear darker than at the center of the image. It is especially common on fast (low-f/number) lenses. I personally like a little bit of vignetting for artistic effect, but it does mean that the lens is collecting less light than it's technically supposed to.



The edges of this photograph are darker due to pronounced vignetting with the Voigtländer 15mm f/4.5 Heliar III lens.

Since vignetting changes the appearance of the overall brightness of the image, it's especially detrimental to video production where one shot might need to match in brightness with another shot, and for this reason cinema lenses often categorize their lenses with T-stops instead of F-stops which account for the "Transmittance" of the lens. Lenses set to equal T-stops should produce images with similar brightness. Vignetting is most common at low f/numbers and on wide angle lenses. If you want to eliminate vignetting, stopping the lens to a higher f/number (smaller aperture) will usually reduce the effect.

Flare

Flare happens as a result of reflections internally in the lens.

It is not possible to completely eliminate reflections off of polished glass surfaces so when bright light enters a lens, it can bounce around and produce flare spots on the image. With astrophotography, flare is rarely an issue since it is not common to see extremely bright light sources in astrophotos. The only instance when flare might occur in an astrophoto is when shooting with the moon in the frame.

The moon is one of the only sources of light bright enough to produce flare in astrophotos.

Lens manufacturers usually apply several extremely thin layers of Magnesium Fluoride or other special materials to the surface of the lens. Each layer of Magnesium Fluoride helps eliminate reflections of a specific wavelength or color of light. Most modern lenses have these "multi-coated" lens elements to try to reduce the occurrence of flare, but it is still possible to find lenses without multi-coated elements.

Flare of the Voigtländer 40mm f/1.4 Nokton S.C.

The Voigtländer 40mm f/1.4 Nokton S.C. (Amazon / B&H) is a single-coated lens that's specifically made to produce more flare than its multi-coated counterpart (Amazon / B&H). The lens is popular for use specifically in photography where the photographer wants to produce lower contrast images. It's an especially well-regarded lens in the black and white photography community because of the way it produces low-contrast shadow details, particularly in brightly backlit conditions. I have owned the Voigtländer 40mm Nokton S.C. and found its characteristic flare to be rather aesthetically pleasing, especially for portraits.

Final Thoughts

I hope this article gave you a practical and hopefully not-too-technical set of knowledge about lens aberrations, how they affect your photos, and a simple way to test your lens's performance. There is a lot more that can be learned about optics out there.