# Understanding Thermal Behavior in Newtonian Reflectors

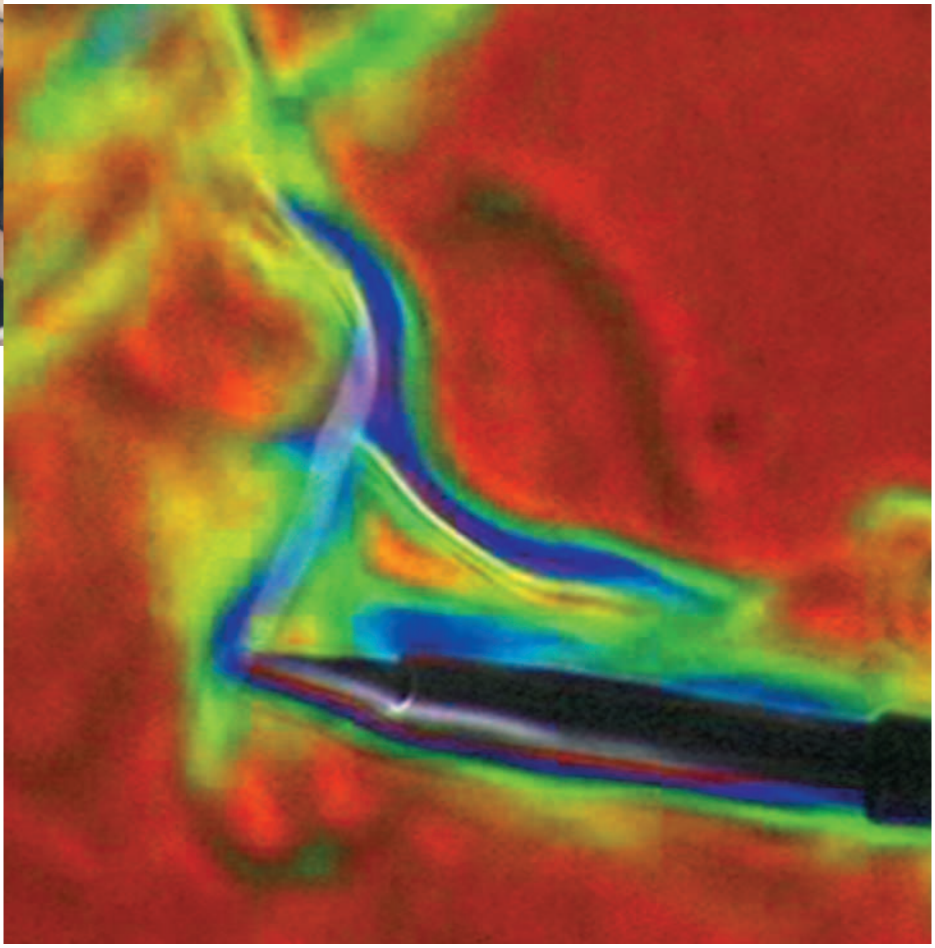
*Even a reflector with first-rate optics will deliver substandard images if thermal problems are not remedied.* | **By Bryan Greer**

**Above:** The author is seen here adjusting the digital video camera used in his schlieren-imaging setup. The video camera is equipped with a special filter and pinhole adapter and mounted on a three-axis positioning stage. With this assembly he was able to study the wavefront errors present while a telescope mirror cools to thermal equilibrium. All images courtesy Bryan Greer.

Thermal problems in Newtonian telescopes are a little like growing old — they're an unpleasant fact of life and one we would rather not dwell on too much. Most of us live in a climate where there are significant temperature differences between indoors and outdoors, or large temperature changes from dusk to dawn. We have learned not to expect crisp images after taking a telescope out of a warm house into the cooler night air. A star test will reveal a dancing, distorted diffraction pattern — the telltale signs of thermal gremlins at work. As telescope users we simply accept this, but a better understanding of what is going on inside your telescope tube is the first step toward a fix.

## Death of a "Refractor Killer"

A few years ago I had an educational, but humbling, experience building a long-focus Newtonian telescope. The goal was to make an instrument so fine it would stand up inch-for-inch to a high-quality apochromatic refractor. My handmade 6-



**Right:** The extreme temperature gradients caused by a hot soldering iron show up in vivid color in the rainbow-schlieren test. Violet hues represent the strongest temperature gradient, and red ones the weakest. Because rainbow-schlieren imaging allows us to "see" heat, it provides an effective tool for understanding thermal behavior.

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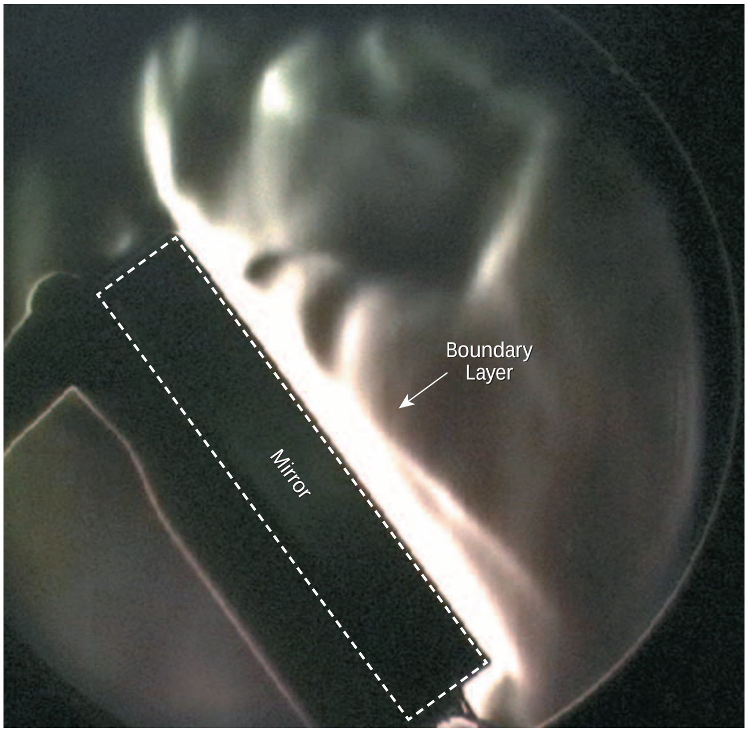
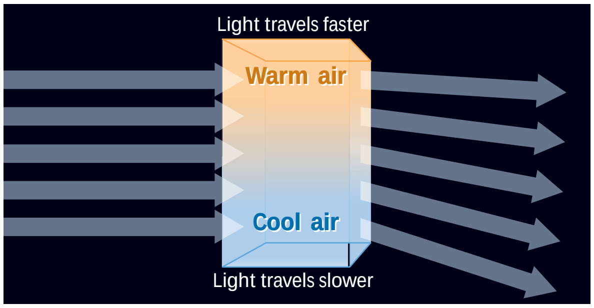


**Left:** A schlieren-shadowgram image of a warm 6-inch Pyrex mirror (edge-on view in dotted outline). It clearly shows the turbulent thermal currents that rob image quality from even the finest optics. In this case, there is a 25° Celsius differential between the mirror and the surrounding air. The *boundary layer* is the region where almost all the heat transfer and wavefront distortion occur. While this may be an extreme example, taking your telescope from a warm car or house out into a cold winter night would create such conditions for a short time.

**Below:** Light travels faster through warm air because it is less dense than cool air. Incoming light will be redirected as it passes through a volume of air of differing temperatures.



inch f/10 mirror was thoroughly tested, and by all indications it was nearly perfect. The long focal length permitted the use of a small secondary mirror to minimize contrast losses resulting from the presence of a central obstruction, and the tube and focuser were well baffled to eliminate stray light.

First light with this scope was disappointing. The image quality was respectable by many measures — perhaps even above average — but it lacked some of the subtle aesthetic qualities I'd grown used to in a high-quality refractor. Side-by-side comparisons often showed the Newtonian's star images not as infinitesimal points, as in the refractor, but as tiny sparkles instead. The first views of Jupiter were not as steady, and the planet's disk seemed to have a softer edge with more scattered light than I had hoped to see. While the star test confirmed that my mirror was well corrected, the diffraction rings appeared more jagged when compared to the refractor under the same skies. My dream of making a Newtonian reflector that could perform like the expensive refractor was not realized. Photons shouldn't care if they're reflected or refracted, I thought. What could be going on with my "perfect" optics?

I continued to observe with this telescope — usually right next to the refractor. Eventually I noticed something interesting. Under just the right conditions, my Newtonian *was* capable of producing an image that was essentially identical to the refractor's. Careful star testing finally showed the same smooth diffraction rings that the refractor exhibited more commonly. My Newtonian was clearly capable of superb images, but why was it so hard to coax them out? The optical figure doesn't change from night to night, and yet this phenomenon was clearly transient in nature. I narrowed the list of suspects down to one: thermal instabilities within the telescope tube itself.

### Thermodynamics 101

In order to understand what is going on inside your telescope's tube, it is helpful to briefly review some thermodynamic fundamentals. Heat can be transferred by any of these three mechanisms: *conduction, radiation,* and *convection.* Conduction is heat-energy transfer through a medium. If you heat one end of a metal spoon, the opposite end will eventually warm up because heat flows along its length. Radiation is heat transferred by energetic photons, mainly in the infrared portion of the electromagnetic spectrum. While this may be the least intuitive mechanism to visualize, just remember the Earth receives all of its energy from the Sun in this manner.

For a Newtonian telescope, the mirror cools mostly by convection. Convection is similar to conduction, except it involves heat transfer between a solid and a moving fluid. (In the language of thermodynamics, gases like air are considered fluids.) Without forced airflow, such as from a fan, the process is called *natural convection.* Unfortunately, natural convection is not a particularly effective mechanism for heat transfer. You don't need to be told this if you've ever patiently waited hours for your warm telescope to cool down.

When convection takes place, there is always a *boundary layer* where the surface of the optic meets the surrounding air. The boundary layer is where almost all the heat transfer takes place, and it is ground zero for image degradation. The most severe temperature gradients exist there. If the temperature of the mirror differs from the ambient temperature, a boundary layer will exist.

People unfamiliar with telescopes are always a little surprised to learn that warm air (or cool air, for that matter) alone can have much effect on image quality. This is understandable. After all, air is invisible, so exactly how *does* it affect the image? Air currents of differing temperatures do their damage by deforming the wavefront of light traveling through the optical tube. In a perfect optical system, the entire wavefront reaches the focal plane at the same instant in time. However, light moves through warm air slightly faster than through cool air since warm air is less dense. If light waves pass through an air mass of nonuniform temperature, different portions of the wavefront will reach the focal plane at different times — the

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light has been refracted and the wavefront will be distorted. An increase in temperature of 1° Celsius will advance the wavefront by about 1⁄50 wavelength for every centimeter it travels. This may not seem like much, but temperature gradients of several degrees are common. Also, if the wavefront is bouncing off a mirror's surface, it will pass through the gradient twice — effectively doubling the error. As we'll see, the cumulative error can be large indeed.

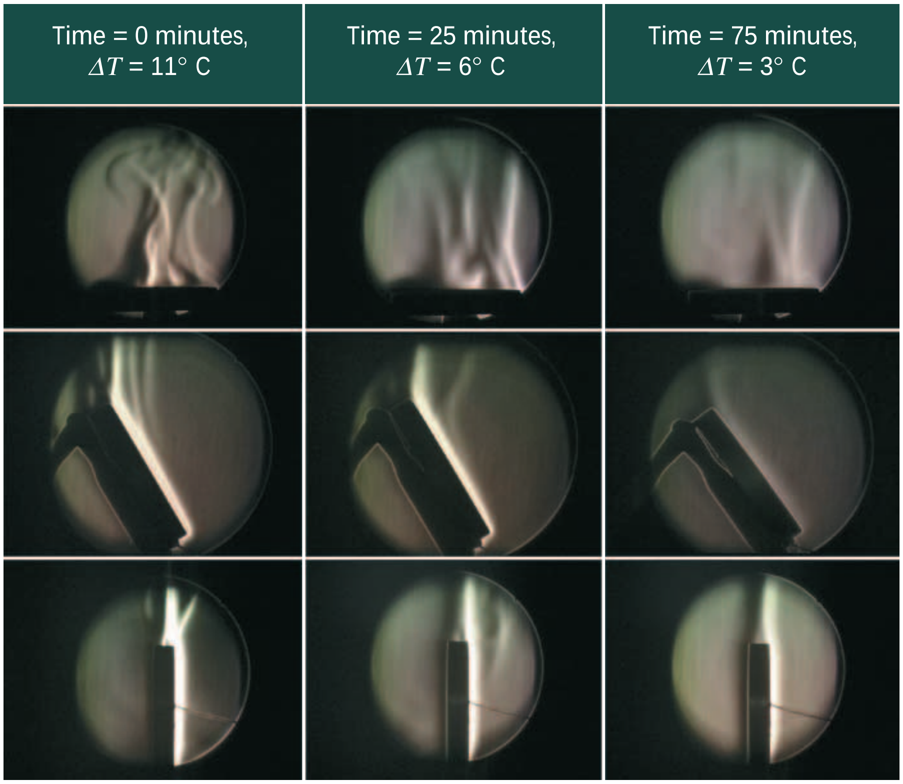
The insidious part of this process is that it is largely hidden. The star test can provide clues, but it still doesn't allow us to really visualize the process. There is much attention given to optical surface accuracy in descriptions of a telescope's quality, but usually little mention of its thermal behavior. However, the time it takes for a telescope to reach thermal equilibrium *does* have a big impact on its usability and even its ultimate performance capability.

## Enter the Schlieren Tests

There is a way to expose the thermal misbehavior inside your telescope's tube. The *schlieren* technique (*schlieren* is German for "streaks") is a close cousin to the Foucault test already familiar to mirror makers. A bright white light is passed through a narrow slit on its way to a large spherical mirror, which returns a collimated cone of light back to the light source. A knife edge is placed at the focus of this returned light, positioned so that it blocks about 50 percent of the returning beam. If nothing disturbs the light, the reference mirror will appear uniformly illuminated. However, a disturbance in the light path will change the intensity of the returned beam. Whether it gets brighter or darker depends on which way the light gets deflected. The schlieren test is very sensitive. A human hand placed in the light path appears to be on fire, and a cup of hot coffee looks like an errupting volcano!

While it is easy enough to see the schlieren shadows with your eye, I employed a digital video camera to record the dynamic thermal flows for subsequent study. In addition, the digital format makes it easier to extract high-quality single frames and even to quantify the results. (Viewing full-motion video of the schlieren technique is even more instruc-

**This series of schlieren images reveals the thermodynamics of a cooling 6-inch Pyrex mirror. The characterization of the airflow depends to a large extent on the mirror's orientation. When the telescope is pointed at the zenith (top row), turbulent flow dominates and most of the thermal disturbance remains in the optical path. Aiming near the horizon (bottom row) produces a more laminar flow. Heat waves were visible for up to three hours after the mirror was placed in an environment 20° C cooler.**



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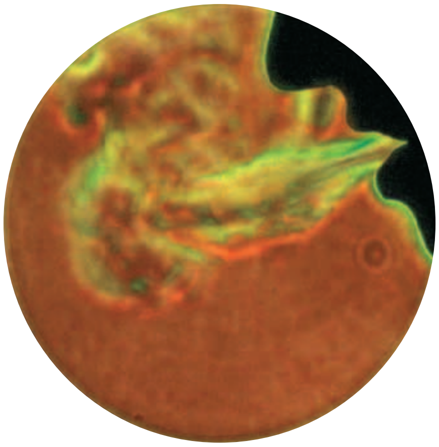


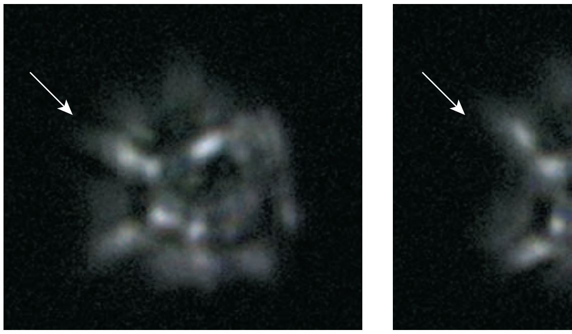
**The author's profile is seen in silhouette here as he directs his breath into the light path of the schlieren test setup. As noted in the text, rainbow-schlieren imaging displays differences in thermal gradient as different colors.**

tive, enabling you to begin to develop an intuitive "feel" for what's going on inside your telescope tube. You can download short video clips of my schlieren trials from my homepage: www.fpi-protostar.com/bgreer/.)

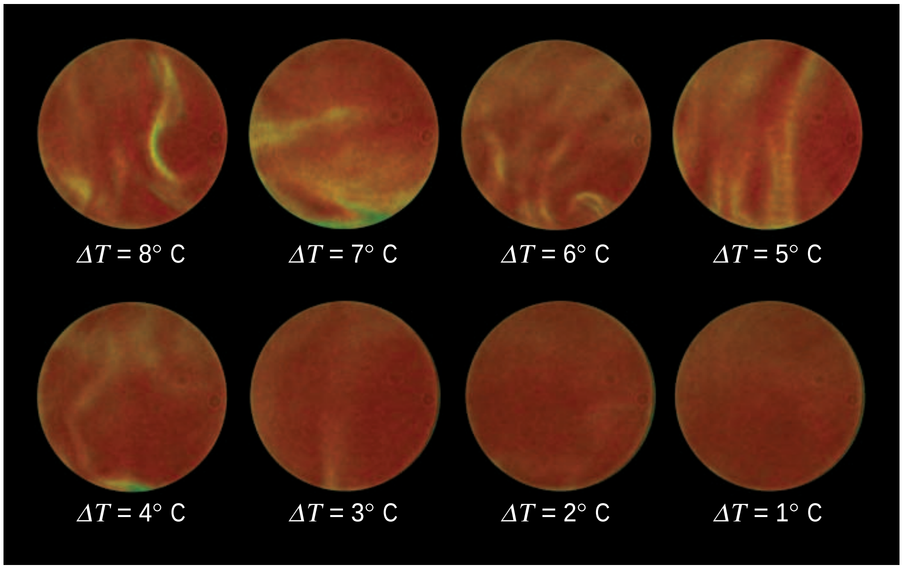
Perhaps it's not obvious how to interpret the schlieren shadows. What correlation is there to observable image degradation at the eyepiece? First, recognize that the schlieren and Foucault tests have similar sensitivities (both are "single-pass" tests, or once-reflected collimated beams), so the schlieren test is the same yardstick we use to measure a mirror's surface errors. The difference between the two tests lies in what is causing the reference light beam to diverge from its intended path. With the Foucault test, it's an imperfect surface on the optic that deflects the light. For the schlieren test, light is refracted by temperature gradients in the air. Either way, the final effect on the image at the eyepiece is the same. You should be as alarmed by a shadow resulting from a thermal gradient as by the same shadow caused by a defect that's actually polished into the glass. It is accurate to think of the moving schlieren shadows as primary ripple in motion. Only when the shadows have almost completely disappeared can we be assured of extracting the maximum performance from the optics.

The amount of time it takes for a mirror to reach equilibrium, thus eliminating the boundary layer, will vary. The size of the mirror, the use of a cooling fan, and the initial temperature difference between the glass and the air are the factors that have the greatest impact on the settling time. An unexpected result of running the schlieren trials was learning how long it takes even a smallish 6-inch Pyrex mirror to reach true thermal equilibrium. For an initial temperature difference of about 25° C, it took almost *two and a half hours* for the boundary layer to disappear! Under real conditions, where the nighttime temperature is constantly falling, it would take even longer. This might explain why some of the most satisfying observing periods with my telescope occurred well after midnight.

It was also interesting to observe the thermal flow patterns and how easily they can be perturbed into a turbulent state. A puff of breath from 10 feet away could briefly disrupt the laminar flow around the mirror. Normal outdoor observing conditions no doubt perturb the boundary layer into a turbulent mode more often than what was observed in my indoor trials.



**This series of rainbow-schlieren images taken over a two-hour period illustrates the many faces of a cooling mirror. The colors represent transverse aberration resulting from light rays being redirected as they pass through the boundary layer. The red areas are the unaltered portion of the returning wavefront, whereas yellow and green are increasing levels of transverse aberration. From the transverse-aberration information, it is possible to make local peak-to-valley (P-V) wavefront error calculations. Where the temperature gradients are strong, as in the top row of images, P-V errors around one wave are typical near the yellow and green regions. Local errors of $^1/_8$ to greater than $^1/_2$ wave are common until the mirror cools to within about 1° C. The final pair of images show that the mirror has cooled to very near equilibrium.**



## Adding Color to the Picture

The white-light schlieren test is educational, but it is only a qualitative tool. It is impossible to assign a numerical value to the wavefront aberrations visible in the shadow patterns. Fortunately, there is a variation of the basic schlieren — the *rainbow schlieren* — that does permit quantification of the resulting errors*. Instead of a knife edge, a radially symmetric rainbow-colored filter is placed at the focal plane. Light that is refracted away from its intended path will pass through a different color on the filter. After calibration and scaling, it is possible to determine peak-to-valley errors from localized regions of the wavefront.

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* *The rainbow-schlieren test should not be confused with the "phase-contrast" method developed by F. Zernike and sometimes called the "Z-test." Zernike's test is describe on page 91 of the original* Amateur Telescope Making — Advanced *book published in 1937 (Albert Ingalls, editor). While both the rainbow-schlieren test and the Z-test produce colorful patterns where aberrations exist, the colors are the result of fundamentally different physical phenomena.*

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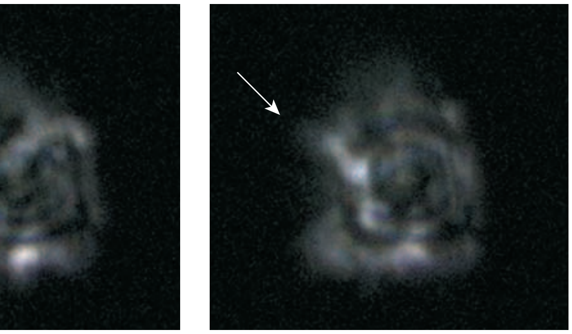

**The star test can reveal the presence of an image-degrading boundary layer even well after the rapid-cooling period. Spikiness in the outer diffraction ring (arrowed) can be caused by either a cooling mirror or atmospheric turbulence. The spikes induced by a warm mirror will migrate much more slowly around the perimeter of the diffraction ring and even appear nearly stationary for several seconds at a time.**

These rainbow-schlieren images show typical errors for a mirror at different stages of cooling. As expected, the most damage is done when a strong temperature gradient exists in the boundary layer. When the mirror shown at lower left was more than 7° or 8° C warmer than the ambient air, the gradient was not only strong but the structure of the boundary layer was typically turbulent. Under these conditions, localized wavefront errors in excess of one wavelength were not uncommon! Fortunately, the mirror is giving off heat at a furious rate during this period, so this situation is relatively short-lived.

An hour or more into an observing session, it is common to find differentials between 2° and 5° C, resulting in wavefront errors varying from under ⅛ to greater than ½ wavelength of light (I used 550 nanometers as the wavelength of visible light). The shape of the wavefront error depends on whether the boundary layer has adopted a laminar or turbulent character. It can be either, and the slightest perturbation can kick a laminar boundary layer into turbulence. I suspect that the delicate nature of the boundary layer is partly responsible for the Newtonian's reputation as a design that is affected by seeing conditions to a greater degree than other telescope types. After watching the layer repeatedly cycle from laminar to turbulent over the course of a few minutes, I understood how this could be misinterpreted as "bad seeing." A refractor, or a sealed-tube catadioptric telescope, will not undergo such dramatic transformations.

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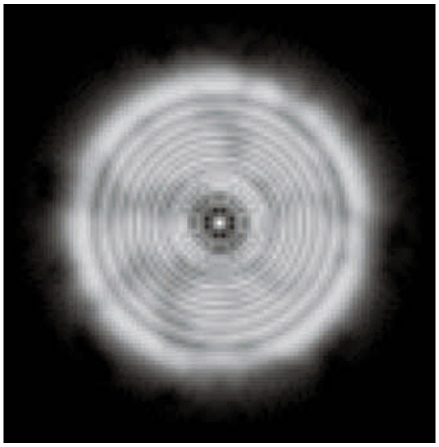
Under near-equilibrium conditions (less than a 1° C difference), the wavefront aberration is less than about ⅒ wave for this 6-inch mirror. At this point, the boundary layer is completely laminar and is doing little to degrade the image. While this mirror was able to reach this point, larger mirrors may not. One example was a 17-inch Dobsonian that never approached equilibrium at any time throughout the night. This scope did not have a cooling fan, though it clearly needed one.

## Field Testing for Thermal Problems

Fortunately, diagnosing the thermal state of a Newtonian telescope requires little more than knowing what to look for. The star test reveals the presence of all but the most subtle boundary layers. Most experienced observers already know the signs of a grossly warm mirror — the strong temperature gradient distorts a defocused star to look like a slowly fluttering candle flame, and in-focus planetary views often show a flare emanating from one edge of the planet's disk. If your telescope has just come from a warm environment, this can last for up to an hour, though it usually subsides in under a half hour. Needless to say, under such conditions your telescope is not performing anywhere close to its capabilities.

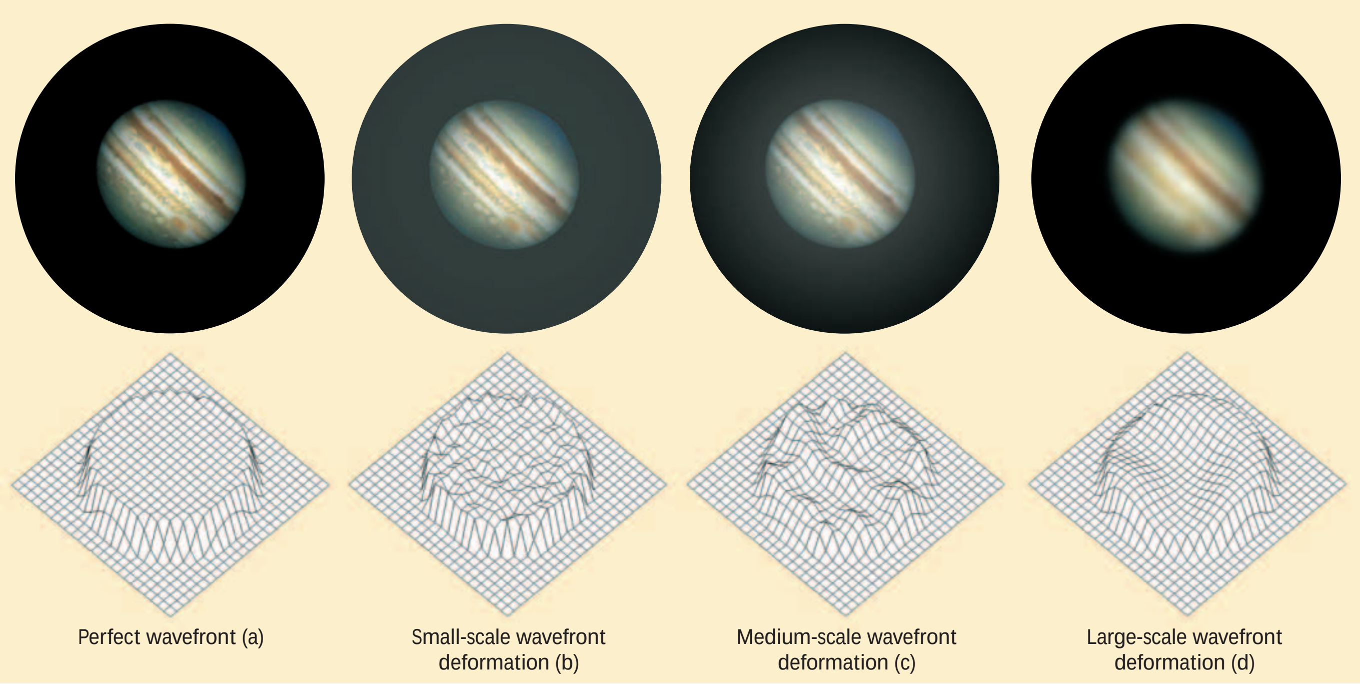


**Defocusing a star image until 10 to 15 diffraction rings are visible reveals slow-moving shadow patterns creeping across the diffraction-pattern disk. Unless the seeing is very poor, these patterns can usually be differentiated from the much faster changing atmospheric distortions.**

After the turbulent cooling phase, it's easy to be fooled into thinking your scope has reached equilibrium. However, the boundary layer has usually just adopted a more laminar structure, making it more difficult to detect. The heat is still pouring off the glass, but it's doing so in a more orderly manner.

Detecting the presence of this quasi-laminar boundary layer requires a more careful examination. Perform the star test on a bright star with a magnification of between 25× and 50× your telescope's aperture (in inches), and defocus until about five diffraction rings are visible. If your mirror has a fair amount of spherical aberration, defocus in the direction of the softest diffraction rings. Look for spikes in the outer ring that appear to slowly migrate around the perimeter. They may even appear motionless for a few seconds. Atmospheric turbulence may frustrate your attempts to see these spikes, but the much slower motion of the thermally induced defects is the giveaway to their origin. Spikes caused by atmospheric turbulence last for only a fraction of a second and appear randomly around the diffraction pattern. Some experience helps, too. If you get into the habit of using the star test in this manner, you'll soon get to know what your telescope looks like under both good and bad conditions.

Another method is to defocus the star even further, until 10 to 15 diffraction rings are showing. If the skies are unsettled you will clearly see the stream of tur-



Perfect wavefront (a)

Small-scale wavefront deformation (b)

Medium-scale wavefront deformation (c)

Large-scale wavefront deformation (d)

**These simulated views of Jupiter illustrate how thermally induced wavefront deformations with varying scales affect the image. A wrinkled wavefront with closely spaced peaks and valleys *(b)* will scatter light far across the field of view. Wider-spaced aberrations *(c)* create a glow around bright objects. Aberrations that smoothly vary across the whole aperture *(d)* will produce an aesthetically "clean" image, but fine detail is lost. Most thermal errors are of the *(c)* and *(d)* type, though a fan can scramble air of different temperatures to approach the *(b)* condition. The effects have been slightly exaggerated in these simulated images for clarity.**

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bulence rushing across the diffraction pattern (sometimes described as the "conveyor belt"). Study the entire pattern and look for a persistent mottled pattern that appears motionless or very slow-moving. You might even notice the pattern drifting toward the top of the tube. If you're able to see these shadowy patterns at all, it's a sure sign that the mirror is still several degrees warmer than the ambient air.

If your telescope has a fan behind the primary mirror, turn the fan on and off while examining a defocused star. If the star-test pattern remains unchanged with the fan on or off, this is a good indication the scope has reached a true equilibrium condition. In particular, look at both the size and number of spikes in the outer diffraction ring. For large Newtonians, this test seems to work best if the fan is directing air at the back of the mirror, rather than drawing it out the bottom. Sometimes energizing the fan will create a circular "merry-go-round" motion in the diffraction pattern. This is a sure sign that the mirror is still giving off heat. Remember that even air in motion will be invisible unless there is a temperature gradient present.

### Effects on Image Quality

Thermal effects adversely affect all telescopes to some degree, but some optical configurations are more problematic than others. Newtonian telescopes have a number of factors working against them.

The light waves in a reflecting telescope travel through the boundary layer twice — before and after reflecting off the primary mirror. This round trip effectively doubles any thermally induced aberrations. For a refractor, the light passes through the worst area only once. Yes, there will be a boundary layer on the inside surface of the refractor's lens, but it exists in a very quiescent and stable environment. Buoyancy forces will keep this layer hugging the lens surface, keeping it more uniform and laminar.

Most Newtonian telescopes are open to the world. They have either open-ended solid tubes or a completely open truss-tube structure. This means air currents, from breezes or people around the telescope, can enter the tube directly. The observer's viewing position can also have detrimental effects if body heat is able to waft into the optical path. The schlieren test shows how easily even subtle perturbation currents can disturb the boundary layer. Thus, a Newtonian can experi-

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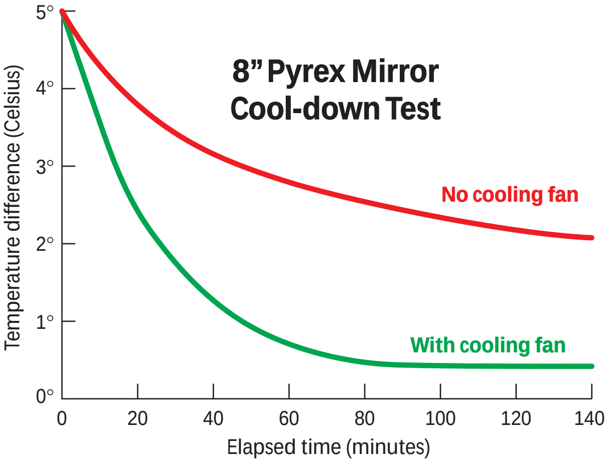


**A fan has a major effect on how long it takes for your telescope to reach equilibrium and how it performs throughout the night. These temperature measurements were taken from a functioning telescope under a clear, night sky while the temperature was falling approximately 2° C per hour. The fan-cooled mirror not only cools faster but also tracks the ambient temperature more closely for the duration of an observing session.**

ence what appears to be more variable "seeing" under some conditions.

Another factor in the refractor's favor is that the light cone begins to narrow as soon as it leaves the refractor's objective lens. Thermal disturbances tend to collect along the tube walls. Warm air rises to the upper tube wall, and relatively cooler air pools at the bottom. Thus, the light path inside a refractor misses the most thermally troubled areas. For Newtonian and catadioptric telescopes, the mirror is located at the bottom of a tube and the incoming light path is parallel to the tube's wall.

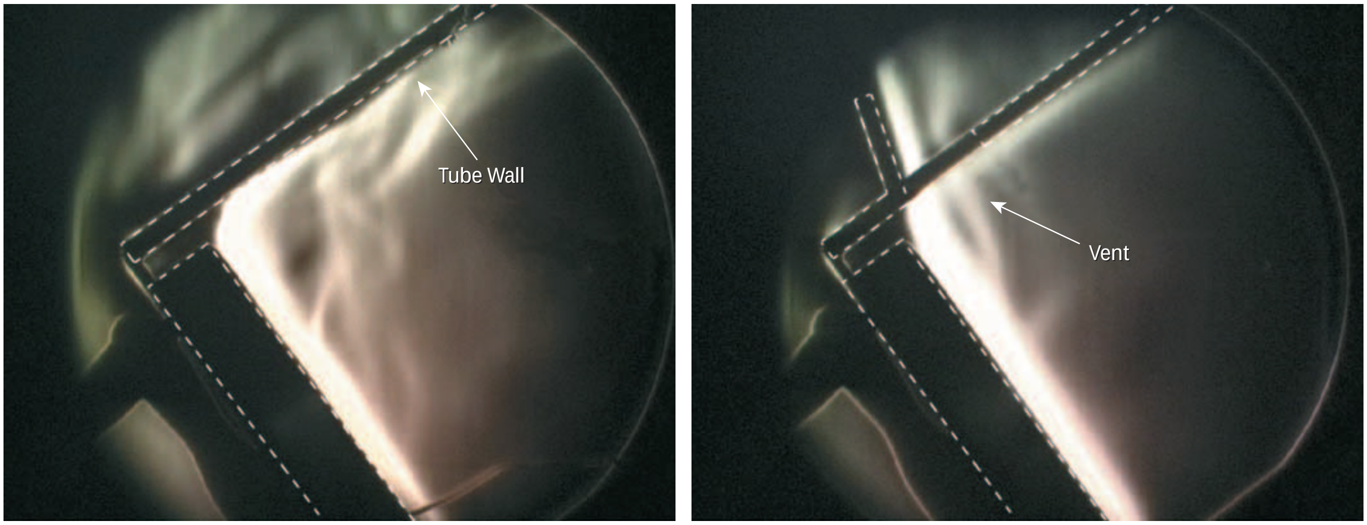
These factors often conspire to prevent the Newtonian from performing as well as optical theory would predict. The cliché "aperture wins" should be true, and yet it is not uncommon to find refractors outperforming larger reflectors when temperatures are falling fast. Of course, refractors have thermal problems of their own. For amateur-size refractors, the most common symptom of a cooling objective is a change in "correction," or spherical aberration. This adversely affects the very fine detail of the image, though the image will otherwise appear aesthetically tidy. Extremely warm refractors can exhibit a turbulent boundary layer in front of the objective lens, but it will subside quickly. Catadioptric telescopes (Schmidt-Cassegrains, Maksutovs, and so forth) share some of the same weaknesses with Newtonians, with the main difference being the sealed optical tube. The sheltered environment keeps the boundary layer in a laminar mode almost exclusively. One disadvantage of a sealed tube is that it can take longer to reach true equilibrium, as the heat usually escapes the tube more slowly.

Thermal problems affect the image quality in different ways, depending on the structure of the boundary layer. A wavefront that is like a finely crumpled sheet of paper scatters light across the entire field while leaving fine detail mostly intact. This kind of contrast loss is given the special name of *veiling glare*. Wavefront aberrations that approach the scale of the whole aperture, like a sheet of paper held at the edges and gently warped, erase fine, low-contrast features from a planet's surface. Wavefront aberrations in between these extremes manifest themselves as a glow around bright stars and planets. (Of course, even under the clearest skies a certain amount of haze around bright objects is unavoidable. It is a result of scattering within your imperfect eye.)

Thermal currents are capable of distorting the wavefront at most of these scales. A laminar boundary layer that smoothly changes in thickness or temperature across the entire aperture will affect only the finest planetary detail. This might go undetected except under the best of seeing conditions. A turbulent boundary layer will redirect some of the light far from its intended path. As a result, light will be scattered across the field of view.

## No Cure, But Many Remedies

Owners of Newtonian telescopes should not be overly distressed by these findings. In fact, there is reason to be excited.



***Left:*** **Here is graphic proof of why it is wise to leave at least an inch of space around your primary mirror. In this example, the telescope tube is only $^{3}/_{8}$ inch from the edge of the mirror, allowing rising thermal currents to remain in the optical path.** ***Right:*** **A tube vent placed above the primary mirror can help eradicate the messy thermal disturbances during the initial cooling period. However, the vent should be kept closed when the mirror is just a few degrees above the ambient air temperature. Leaving it open can permit external breezes and other sources to disturb the boundary layer, resulting in a temporary increase in image degradation.**

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After all, identifying and understanding a problem is the necessary first step toward solving it. While it may be impossible to consistently eradicate the boundary layer, there are ways to minimize the detrimental impact.

Big improvements are possible if you use a fan. Fans are commonplace on large Newtonian telescopes, but you should consider using them even on small reflectors. Without a fan, the 6-inch mirror used in this testing was still cooling well after two hours into the trials. Forced convection increases the heat-transfer rate manyfold and results in the mirror reaching equilibrium much faster. Since the air temperature is continuously falling on most nights, it is advisable to continuously operate the fan throughout the observing session (especially on large scopes). This will keep the residual temperature difference between mirror and air to a minimum. After installing a fan, examine the Airy disk of an in-focus star at high magnification to ensure there are no vibration problems caused by a slightly misbalanced fan.

There is a belief among telescope makers that sizing your tube to provide for at least one inch of clearance between the edge of the primary mirror and the tube wall is a good idea. For example, an 8-inch reflector should use at least a 10-inch tube. This is sound advice. During the early stages of cooling, the turbulent flows emanating from the mirror collect along the upper tube wall and spill partially into the optical path. In the example pictured at left, the telescope tube is only 10 millimeters from the mirror’s edge, and there is clearly insufficient space to keep the messy thermal flows out of the optical path.

Open mirror-cell designs also have merits. The schlieren images show that a significant amount of heat transfer takes place on the backside of the primary mirror. In fact, when the mirror is standing vertically (that is, the scope is pointed at the horizon) about one-half of all the heat transfer takes place at the rear boundary layer. However, this can happen only if the back of the mirror is left exposed to the surrounding air. Gluing a mirror to a solid disk of wood will result in longer cool-down times and a larger quasi-static temperature difference during times when the ambient temperature is falling.

Of course, cool-down time will be related to the mass of the mirror. Thin mirrors do more than just save weight — they also cool significantly faster. The effort required to produce and support a thin mirror is well worth it. Perhaps more important, a thin mirror will track the falling ambient temperatures more closely.

If you have a truss-tube or open-structure telescope, you should observe with the shroud in place. This will help prevent your own body’s heat from entering the optical path. If you can, position yourself downwind of the tube. These practices are especially important when you observe in cold conditions.

A strategically placed door, or tube vent, directly above the mirror can be employed, but the results are mixed. When the mirror is far from equilibrium and rapidly cooling, a vent will help expel the warm air from inside the tube. This is especially effective at keeping the turbulent warm air from accumulating along the upper tube wall and entering the optical path. However, the vent is of less benefit — and it can actually hurt the image — once the mirror has cooled to the point where the boundary layer settles into a laminar condition. Leaving a vent open during this phase can result in even more disruption of the boundary layer from air currents outside the telescope. The best advice here is that if you do employ a tube vent, make sure you can close it.

Choose materials and locate components with thermal consequences in mind. Besides the optics, other components of the telescope can store heat too. Try to keep large, dense masses out of the optical tube or where they may convect heat waves into the optical path. Dobsonians frequently employ a heavy counterweight or battery near the primary. If possible, locate these outside the optical tube.

The schlieren tests are ongoing, and future exploration should provide a more detailed understanding of the issues described here. My dream remains unchanged. I still want to build a telescope that can exploit the inexpensive aperture advantage of the Newtonian design but with the repeatable out-of-the-case performance of a quality refractor. Perhaps the “refractor killer” isn’t dead after all.

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