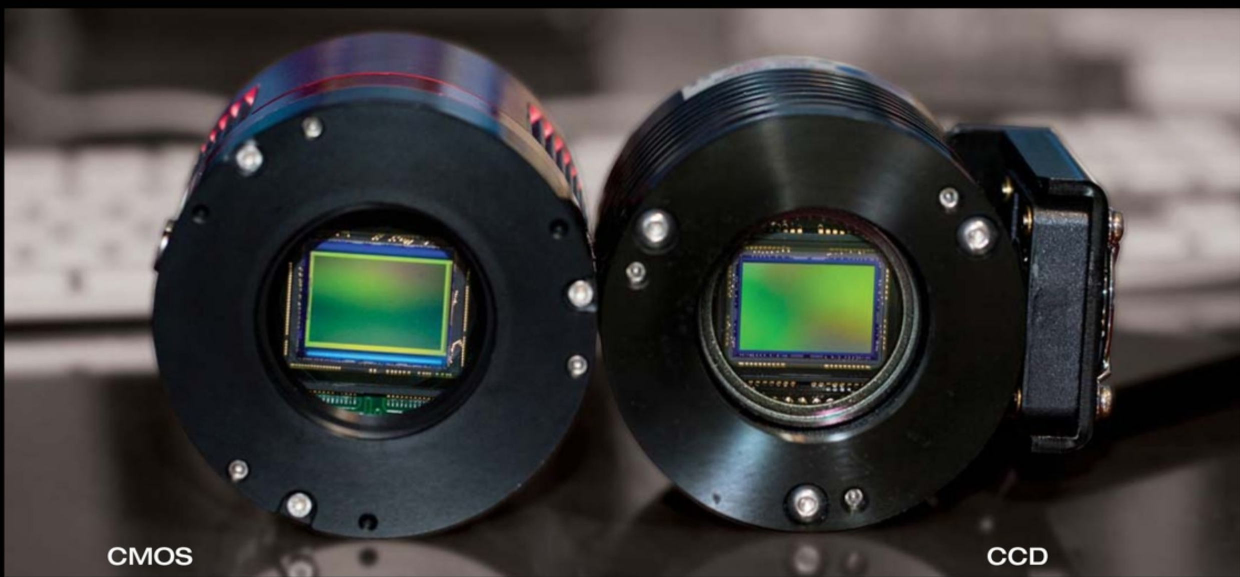
Changing of the Guard

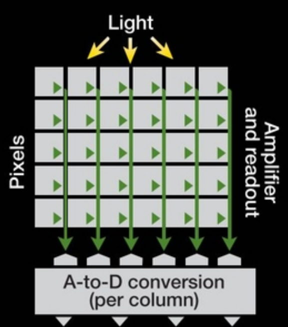
CMOS is set to become the dominant scientific-imaging medium — but is it up to the task?

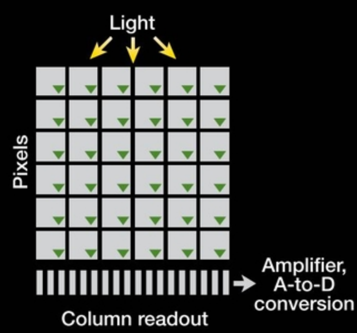
It wasn't that long ago that photography went through the major transition from chemical film-based emulsion to digital cameras. I remember well an editor of a computer magazine who would regularly pontificate about how ridiculous it was that anyone thought digital cameras would ever match the quality of film. He'd quote numbers that compared the sizes of pixels to film grains, highlighting the various shortcomings of digital cameras at the time, and to some degree he was right. What he didn't foresee is how quickly these shortcomings would be overcome. This is a cautionary tale, of course, to anyone watching the current transition from CCD-based image sensors to CMOS, a transition that's in full bloom for the astronomical imaging community.

Every technological advancement experiences growing pains, and the current transition in digital imaging from CCD to CMOS technology is no exception. Both charge-coupled devices (CCDs), and complementary metal oxide semiconductors (CMOS) sensors work on the same basic principles of physics. Specially treated silicon is laid out in a rectangular or square grid of "pixels." When light hits



▲ **HARD TO TELL** It's virtually impossible to see the difference between a CCD and CMOS camera. At left is a ZWO ASI071 CMOS camera, while the camera at right is a Starlight Xpress Trius 26C CCD.





◀▶ **UNDER THE HOOD** Although CCD and CMOS detectors function in largely the same way, one important difference is how they read out signal. A CCD (right) moves electrons (green arrows) off the detector in rows. The electrons are then sent off-chip to the amplifier and analog-to-digital converter. By contrast, the CMOS detector (left) has an amplifier behind every pixel and an A-to-D converter for each column.

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one of these pixels, it receives a small electrical charge. The more light, the higher the charge. At the end of an exposure the pixels are read out, and each pixel is assigned a numeric value that increases with the amount of charge collected. This produces a two-dimensional record of the various light intensities across a plane in a format that a computer can display as an image. In this way (and only this way), both CCD and CMOS are essentially doing the exact same thing.

PRETTY PICTURES CMOS astronomical and DSLR cameras are perfectly capable of producing gorgeous deep-sky images. This image of M45, the Pleiades, was recorded with a CMOS-based modified Canon EOS 5D DLSR camera and Officina Stellare Veloce 200.

The Other Shoe Drops

The vast majority of image sensors used in our astronomical cameras are made by only two vendors, On Semiconductor (originally Kodak), and Sony. These two companies make the sensors used in many industries besides astronomy. In fact, astronomy is a tiny niche market for these manufacturers — automated manufacturing, security, and traffic monitoring are all multi-billion-dollar industries by themselves (some modern automobiles have as many as 20 image sensors!). The largest demand for imaging sensors is, of course, cellphones. One recent report stated that there would be over 6 billion cell phones in operation in 2020, with a market worth at least $335 billion. Astronomy is only a flea on the back of a very large cash cow.

In a surprise move late last year, On Semiconductor announced it is suspending production this year at its only remaining plant capable of making CCD sensors. The former Kodak CCD facility in Rochester, NY, will then cease operations in June 2020. Only a few years ago, Sony announced the discontinuation of CCD sensors but extended the life of its current chip offerings up until 2025. And while Sony is continuing to produce CCDs, it's no longer developing any new chip designs.

CMOS is the future of digital imaging, but why? Although both technologies do essentially the same thing with pixels and photons, the similarities end there. For starters, manufacturing technology for semiconductors has improved to the point where it's easy to integrate more circuitry onboard the image sensor. More of the supporting electronics can be bundled right on the same chip, making CMOS sensors much more flexible in terms of electronic design and capabilities. This extra integration makes the surrounding electronics design simpler as well, and more room for gates (the fundamental building blocks of integrated circuits) allows for a tremendous increase in readout speed. CMOS sensors are also smaller and consume far less power than CCDs — fewer supporting electronic components means smaller packaging.

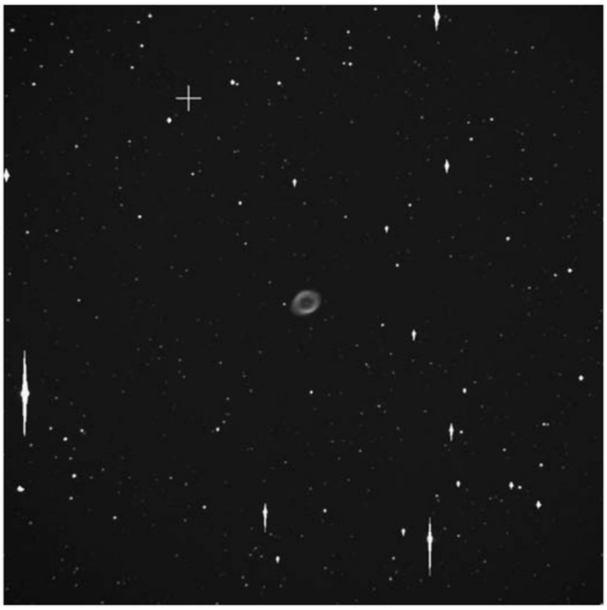
All these differences contribute to a manufacturing process for CMOS technologies that costs much less than it does to make CCDs.

So, CMOS is smaller, costs less to make, works faster, and consumes less power — a paramount factor for today's battery-driven world. With these kinds of advantages, you might well wonder why we are bothering with CCDs at all anymore. You would not be the only one.

The Road Ahead

Although CCD technology is older, it has some advantages over CMOS-based cameras when it comes to low-light photography. These advantages are shrinking quickly, though, and one industry insider recently stated that even Sony was surprised with how quickly the security-camera market abandoned CCDs in favor of their newer CMOS offerings.

One way that CMOS is already completely on a par with CCDs is in Quantum Efficiency. QE is a measure of how efficient a sensor's pixels are at converting individual photons into electrical charge. A sensor that registers half the light

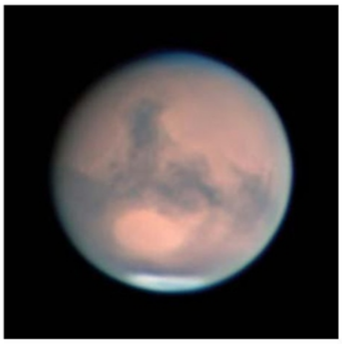


SIGNAL OVERFLOW CCD detectors used for astronomical research are almost without exception linear detectors, meaning they record light in a predictable, linear manner. Linear detectors often display "blooming spikes." Such overflow of signal from saturated pixels can be seen in this exposure of M57, the Ring Nebula, in Lyra.

falling on it has a QE of 50%, while one that records ¾ of the light has 75% QE. The higher the QE, the better the sensor is for low-light applications. Early CMOS sensors had relatively poor QE compared to CCDs at the wavelengths astronomers are interested in and were generally poor choices for any kind of low-light imaging. Today, the top CCD and CMOS sensors are now flirting with QE's in the 90% range, meaning that there is no inherent QE advantage to either technology.

Another technical limitation of CMOS that has vanished in recent years is *read noise*. Read noise is a slight random fluctuation in data values that occurs as an image is read off a detector. Both CCD and CMOS started life with very poor read-noise performance, and CCDs were well ahead of CMOS for many years. Today, CMOS read-noise performance has caught up with and even surpassed most CCD designs. This tiny bit of noise has a very big impact on low-light applications in which the faintest signal is being sought, and so it's no small consideration for the astronomical market.

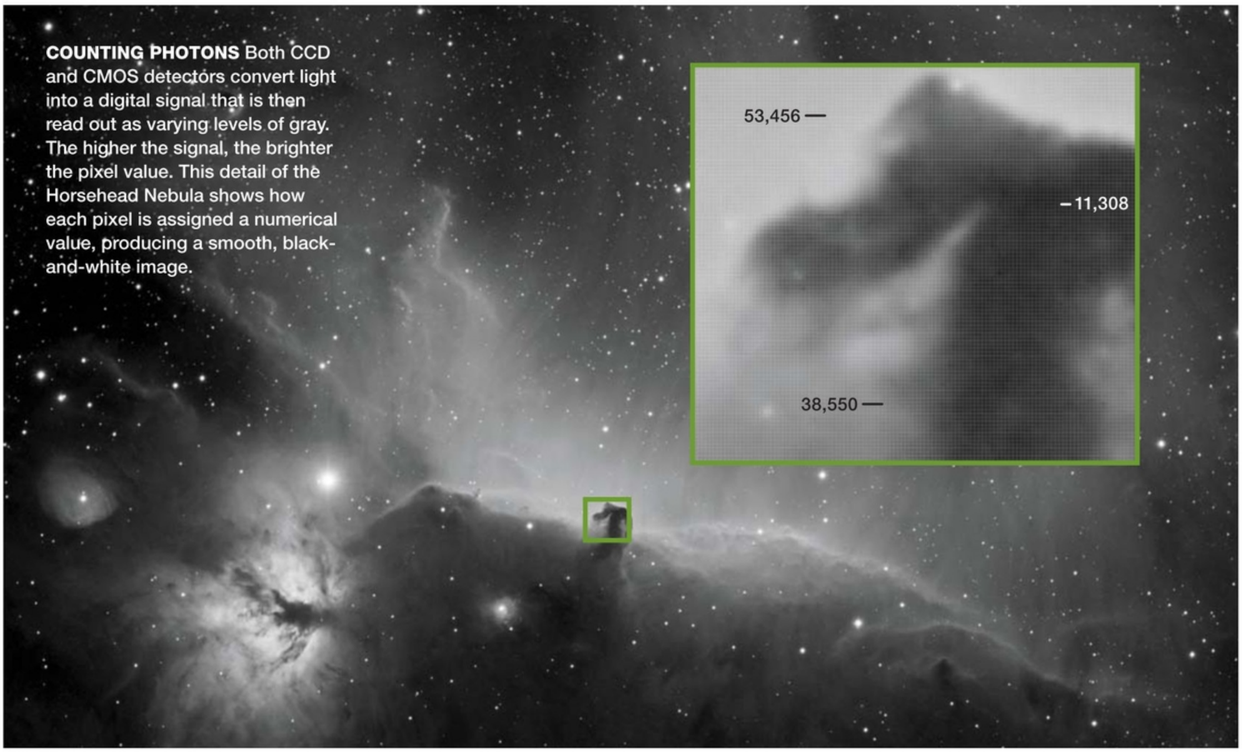
One weakness for low-light imaging with CMOS that is seeing rapid improvement is *amp glow*. A CCD detector requires an output amplifier in its supporting electronics that is part of the analog-to-digital conversion necessary to



◀ **ALREADY BEST** CMOS detectors are vastly superior to CCD technology when it comes to readout speed. CMOS active-pixel designs are inherently useful for the "lucky imaging" technique of planetary astrophotography, in which hundreds of frames per second are recorded to capture the sharpest frames during the best moments of steady seeing. This detailed image of Mars was captured with a ZWO ASI120MM CMOS planetary camera and 12.5-inch Newtonian reflector recording 133 frames per second.

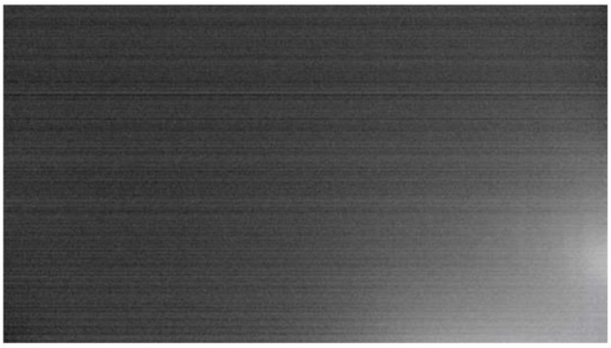
convert the collected photons to a digital signal. CMOS incorporates a single amplifier behind every pixel, meaning there are millions of amplifiers on every CMOS detector. It turns out that all those extra integrated electronics get warm and produce a lot more heat when the sensor is in operation. This heat shows up as a glowing pattern radiating out from the edges of the chip during long exposures — amp glow. Subtracting a dark frame during calibration can mitigate this, as it does with CCD calibration to some degree. But it is not 100% repeatable with CMOS images, and dark-frame subtraction will often leave some residual thermal signal that must be removed manually during post-processing. In addition, this accumulated thermal signal robs the chip of its ability to detect extremely faint objects, because these pixels are filling up too fast with polluted signal and noise.

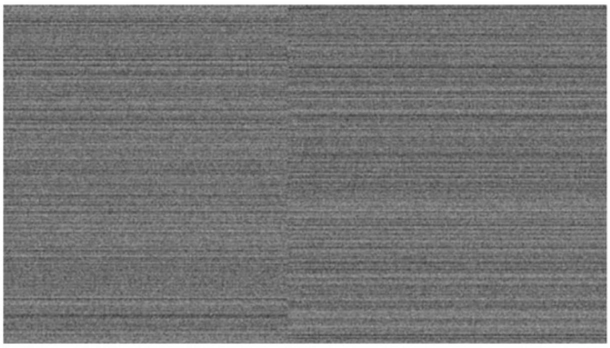
Amp glow is strong even in some very recent CMOS



COUNTING PHOTONS Both CCD and CMOS detectors convert light into a digital signal that is then read out as varying levels of gray. The higher the signal, the brighter the pixel value. This detail of the Horsehead Nebula shows how each pixel is assigned a numerical value, producing a smooth, black-and-white image.

MARS: SEAN WALKER / S&T





▲ *Left:* Problems with CMOS sensors only become apparent during long exposures. This dark frame is stretched to display the amplifier glow at bottom right. *Right:* Another problem with CMOS detectors used for scientific imaging is that they produce non-repeating fixed-pattern noise. Note how the dark pattern noise has shifted between frames. High-quality and newer CMOS cameras are doing much better at reducing this issue to near-imperceptible levels.

designs, but many newer sensors exhibit amp glow that is quite low, and some camera vendors are doing "tricks" with the electronics to keep it to a minimum. One scientist who is searching for ultra-faint targets tells me there is currently no CMOS sensor on the market that performs adequately for his very exacting work. I'll have to check in with him again in five years and see if this is still the case.

The last significant issue that CMOS has yet to overcome is the non-linear sensitivity to light. When we talk about linearity of a sensor, we are talking about the ratio of the signal recorded to the signal that was received. If you dump in twice the amount of light, you should get twice the amount of signal. CCDs that are intended for scientific use are 100% linear (non-antiblooming), so that when the signal is so high that they saturate, they spill the excess charge into adjacent pixels, called blooming spikes. Many CCD detectors used for astrophotography include an anti-blooming gate to redirect overflow charge and lose their linearity only at the upper end of their exposure range. CMOS sensors, on the other hand, are non-linear throughout much of their range. This varies from sensor to sensor. How this affects astronomy is that flat-field calibration, which corrects for pixel-to-pixel sensitivity differences, among other things, does not always work well with CMOS sensors; the math just doesn't work. Also, if your intended use is photometry (accurately measuring the brightness of a target), your calculated values may be suspect. They are likely close, but not as rigorous as if determined from a truly linear sensor.

If your goal is simply aesthetic astrophotography, sensor non-linearity is often negligible or can be mitigated in post-processing. Often, it's very slight (CMOS is still far superior to film). Of course, it requires more work than having a properly calibrated image in the first place, but it's not a show-stopper. I've seen some academic work recently in which this is the subject of intense research, and I wouldn't be surprised if technological advancements solve this problem within a generation or two.

Finally, another commonly discussed issue with CMOS sensors is *fixed-pattern noise*. Both CCD and CMOS sensors have fixed-pattern noise, often noticeable during longer exposure shots when particular pixels are susceptible to giving brighter intensities above the general background noise. This is easily removed by calibration with a bias or dark frame on a CCD sensor. With some CMOS cameras, the pattern noise often varies from frame to frame, and since it's not repeatable, it can't be simply subtracted. However, a lot of this pattern noise has more to do with the surrounding electronics implementation than it does with the sensor itself, and camera vendors are gaining more experience in taming this beast for our market. For example, the issue is already a nonfactor for most commercial DSLR cameras, as well as the latest generation of cell phones capable of low-light imaging.

Onward into the Future

Technological progress is often fraught with growing pains, false starts, and compromises. There are still and possibly always will be some applications where CCD-imaging technology works best, such as in space where radiation hazards are very harsh on delicate electronics. To be sure, there will be manufacturers willing to meet that need for a price. For those of us on Earth without government-sized budgets, the juggernaut of CMOS is well beyond critical mass now. Clearly, the Sun is setting on CCDs for amateur astronomers and most ground-based imaging applications.

But I wouldn't be in a hurry to toss out your old CCD cameras. The current generation of CCD cameras is going to be available for a few more years yet, and it will offer some important advantages for the discerning imager. While CMOS sensors are still not quite up to the challenge of many kinds of scientific imaging, we can say confidently that they are getting very large in the rear-view mirror.

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