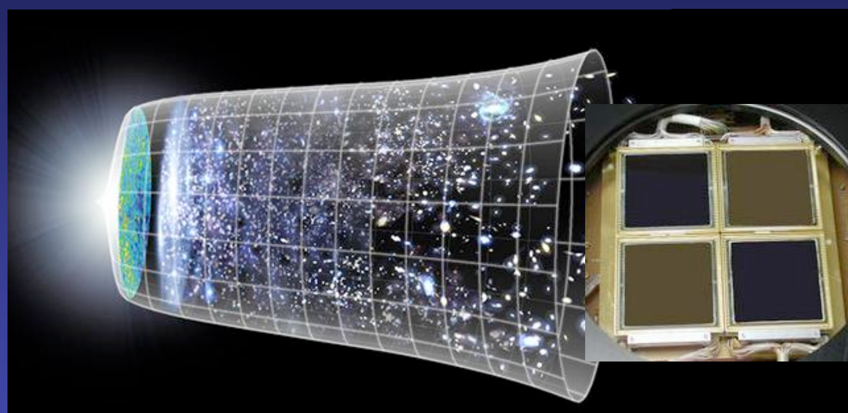
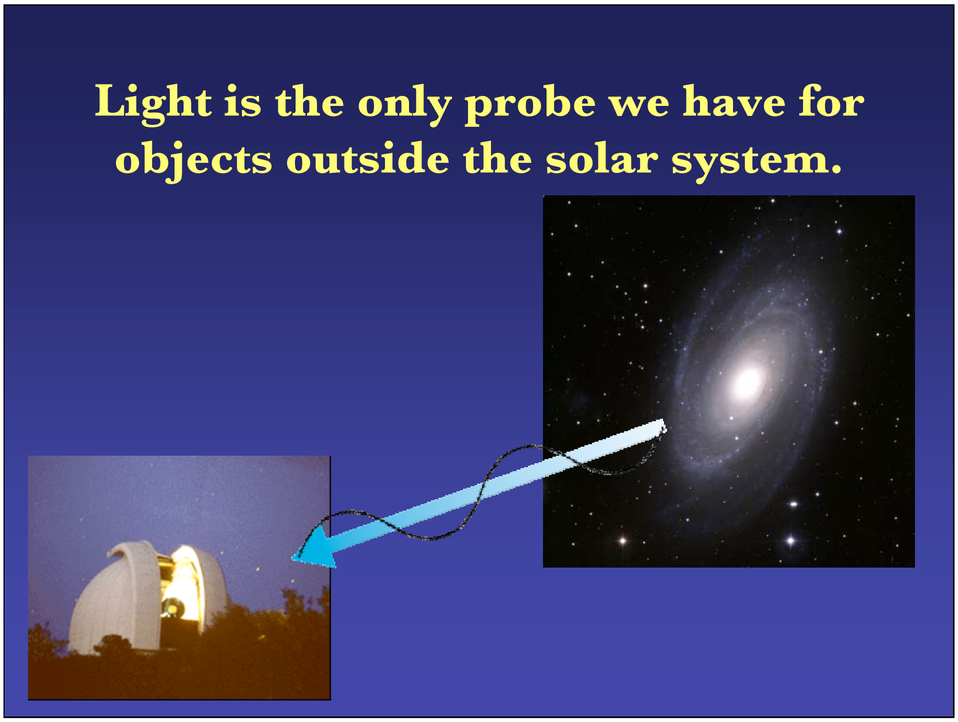
Studying the Universe with CCDs



Dr. Kurtis A. Williams
Steward Observatory



For objects within our solar system, we can study them by sending robots or by bringing bringing samples back to Earth for study. For objects outside the solar system, light is the only thing we can collect.

The main purpose of telescopes is not to magnify objects, but to collect more light so that fainter objects can be seen.

Astronomers only get a few nights at the telescope and need to save that light for analysis at home.

MMT Observing Schedule
January 2005

Date*		Day	Moon	Observer	Instrument
1	(12.0)	S	-7.8	Landt	Blue Channel
2	"	S	-6.8	"	"
3	"	M	-5.9	Secondary Change / McLeod	Megacam
4	(11.9)	T	-4.9	Calvet	"
5	"	W	-4.0	McLeod	"
6	"	Th	-3.0	Papovich	"
7	"	F	-2.1	"	"
8	"	S	-1.1	Holman	"
9	"	S	-0.2	"	"
10	"	M	0.7	K. Williams	"
11	"	T	1.7	"	"
12	(11.8)	W	2.6	"	"
13	"	Th	3.6	Holman	"
14	"	F	4.5	"	"
15	"	S	5.5	de Jong	"

(Prof. Debra Elmegreen, Vassar)

The vast majority of professional telescopes are shared by astronomers at multiple institutions. Any given astronomer therefore only gets a handful of nights every year.

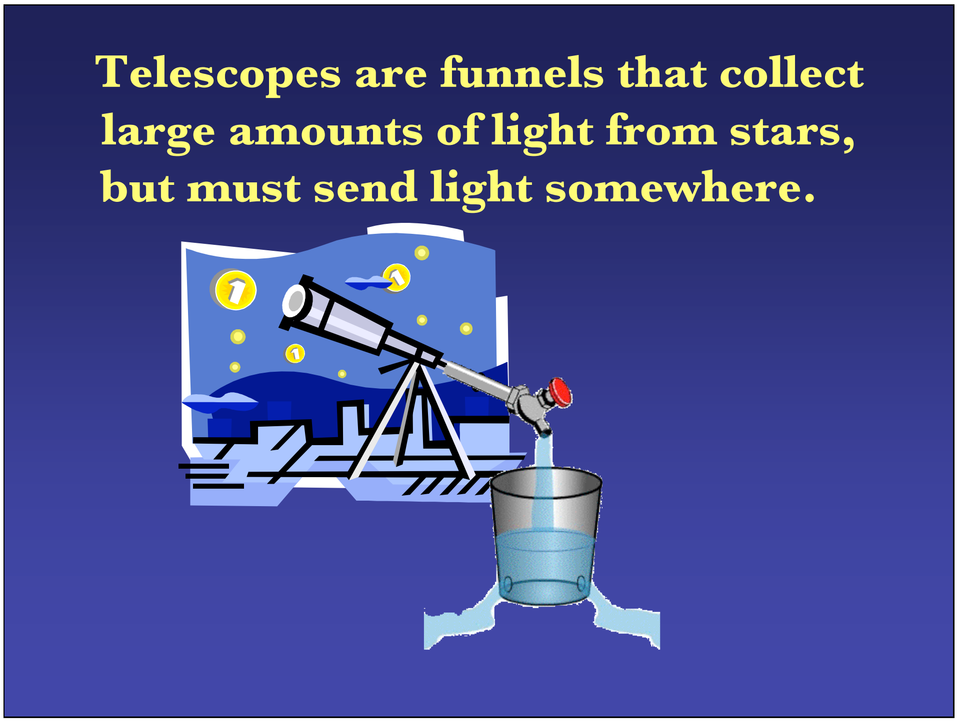
The schedule on the left is for the MMT telescope on Mt Hopkins, south of Tucson, Arizona. The highlighted area shows my only time on the MMT during that year. During those three nights, we had two clear nights to take pictures. During those two clear nights, I took about 50 gigabytes of data and put it on to tape.

The image on the right, of astronomer Debra Elmegreen, shows what astronomers tend to do 90% of their time -- sit in front of a computer and work on the data that we took on the clear nights.

There are many different ways humans detect and analyze light -- with our eyes, with film cameras, video cameras, copy machines, etc., etc., etc. So, what is the preferred way astronomers collect their light?

Charge-coupled devices are the main imaging device astronomers use to collect light and store it. These "CCDs" are put in cameras at the back of a telescope, and electrical signals detailing the image are sent to a computer in the telescope control room.

But, why do astronomers use CCDs?



All a telescope does is take light from a large area (the “effective aperture” of the telescope) and concentrate it down into a smaller area where astronomers can make use of it. If there is nothing located at the exit of the telescope, the light will just flow out into the dome and be lost.

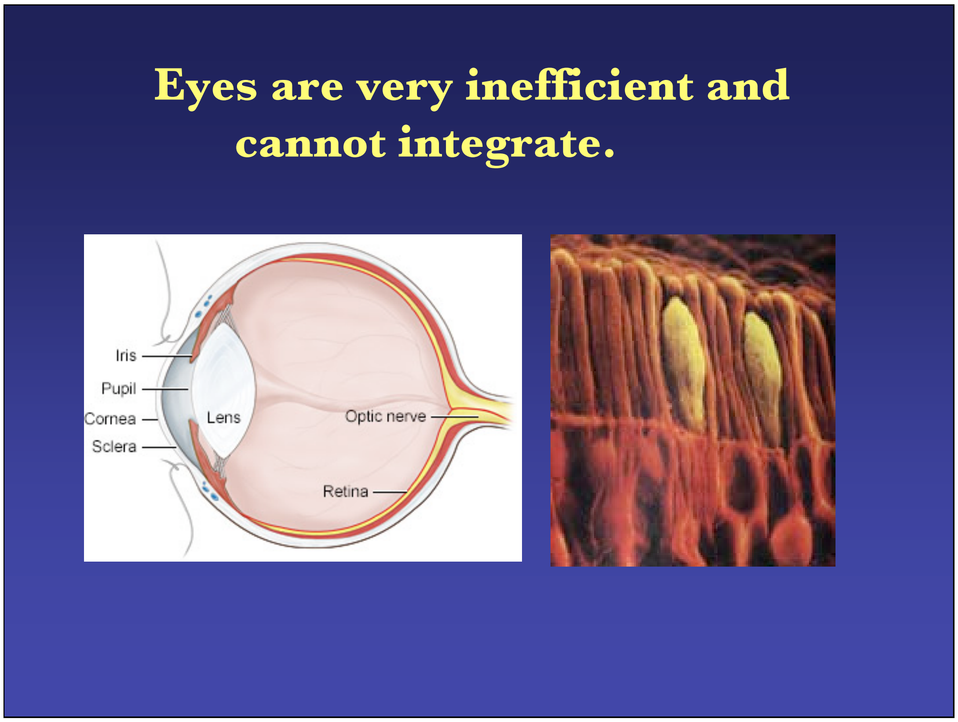
Right after the invention of the telescope, astronomers used their eyes to observe the light their telescopes collected. This light was then processed by their brains for analysis, with the results stored on paper.

Some examples:

William and Caroline Herschel (brother-sister team, late 1700s, England) used various telescopes to look for clusters of stars and "nebulae." Their observations were collected by Johan Dreyer in the late 1800s to form the basis of the "NGC" catalog. Often William would do the observing and Caroline would take notes, but sometimes Caroline would do her own observing.

Maria (Muh-RYE-uh) Mitchell (1818-1889) -- first professional female astronomer in U.S; discovered a comet, hypothesized that Jupiter is made mostly of clouds instead of a large version of the Earth with only a thin atmosphere.

Heber Curtis (1872-1948) -- Proposed that other galaxies were "island universes" made of stars. One of the last astronomers to use the eye for observations.



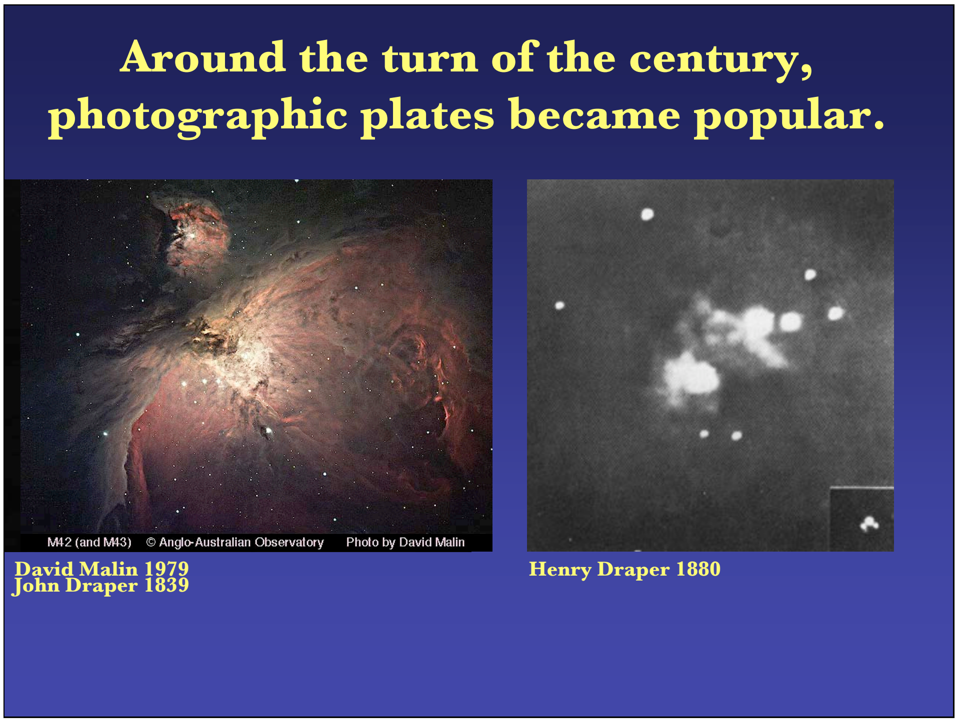
How faint we can see depends on how many photons we can collect. The faintest stars we can see put 300 photons/second in one spot in our eye, and our eye “refreshes” about every 1/10th second. If we could make our eye refresh only once a second, we could see 10 times fainter.

Our eye can detect single photons, but the brain requires mutliple photons to “see” an object. If we could see an object with just one photon, we would instantly see 30 times fainter!

What is the difference between the bright stars of this image and the faint stars? Between the blue stars and the red stars? Our eyes alone can only give a qualitative answer to these questions, but in science we want quantities. How many times brighter are the brightest stars? How much bluer are the blue stars?

Look at the checker board. Is square A or square B lighter? Actually, they are both the same. The brain uses cues from surrounding material to interpret what it sees. This is great for our lives on Earth, but we can be tricked.

The most famous optical illusion in historical astronomy are the supposed “canals” on Mars, strongly supported by Percival Lowell. He was convinced that he saw thin lines on the surface of Mars, but these days we know that those lines aren’t there. Many theories exist for what Lowell was really seeing -- blood vessels in his own eye, tricks from poor optics in the telescope. What we learn most from this is that the eye/brain combo is not the most accurate/reliable means of doing astronomy.



The first known photograph of an astronomical object is this picture of the moon (left) by John Draper in 1839. His son, Henry Draper, took the right-hand photograph of the Orion Nebula in 1880. This is the first known photograph of an object outside our Solar System.

The final image is a 1979 image of the Orion nebula showing how much astrophotography improved over 100 years, but it was taken near the end of the heyday of plate photography.

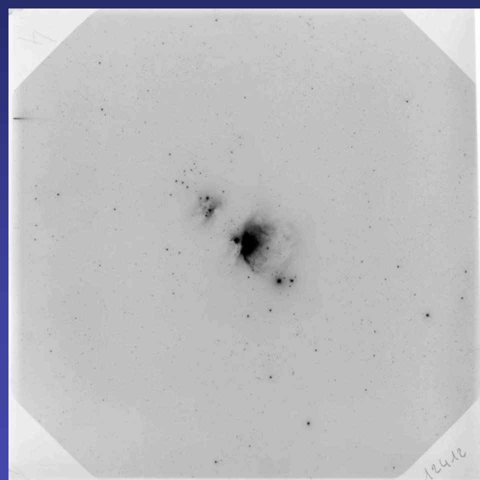
Plates can integrate and are modestly efficient.

“Integration” means leaving the shutter open for long periods of time. If your camera stays still, you get star trails, but if your telescope tracks the Earth’s rotation, the object stays still.

A single plate could integrate until the glow from the sky started to be detected on the plate (“sky fog”). Often this involved the astronomer riding in a cage high in the telescope to make sure the telescope stayed guiding. It was boring and very cold!

Photograph is 2 hours, centered on the North Pole. The foreground, illuminated by the moon, is of Mauna Kea. The observatories are visible on top. Photo was taken from Mauna Loa.

Plates store images accurately for long periods of time.



Taken in early 1970s. Even plates from around 1900 are still usable, though on some the film is starting to peel off the glass backing. If conserved, however, the plates can be used indefinitely. This allowed the astronomer to take data back home and work during the day, when she was more awake.

Plates cannot be added together, making analysis hard.

CCDs are the modern astronomer's weapon of choice for observing.

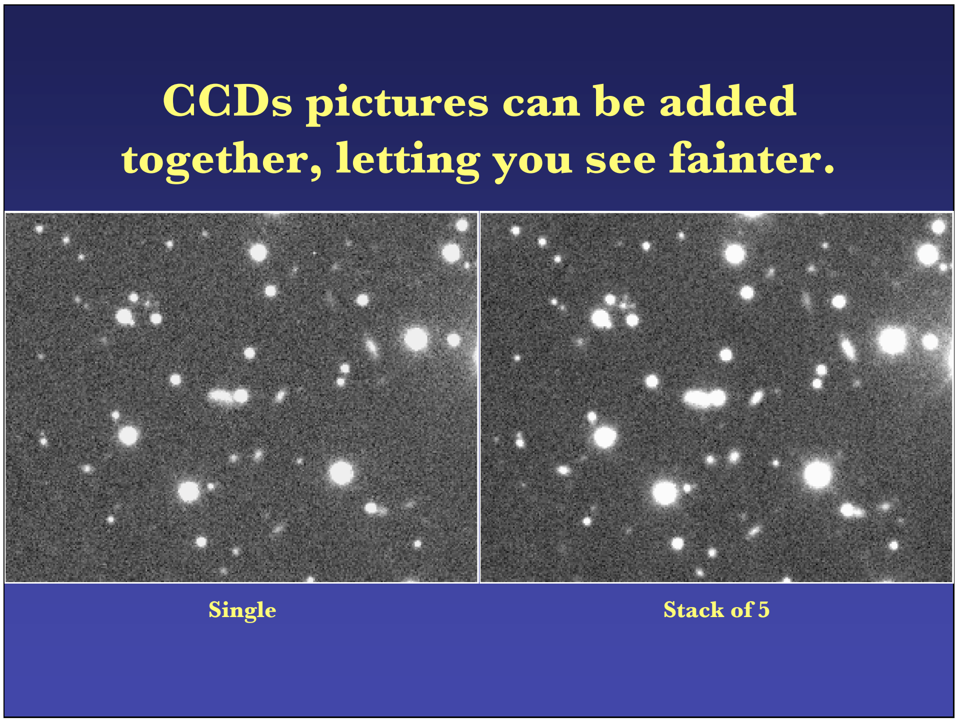
During the 1980s, CCDs won the showdown with photographic plates and became the primary means of collecting astronomical data.

Like photographic plates, CCDs can integrate for long times with little noise. Since the astronomer can sit in a warm room, staying awake all night can be a problem.

Photographic plates tended to only collect 2%-5% of the light that fell on them, where CCDs can collect 80-100% of the light that falls on them. This allows the astronomer to see fainter objects with CCDs than plates -- the whole name of the game!

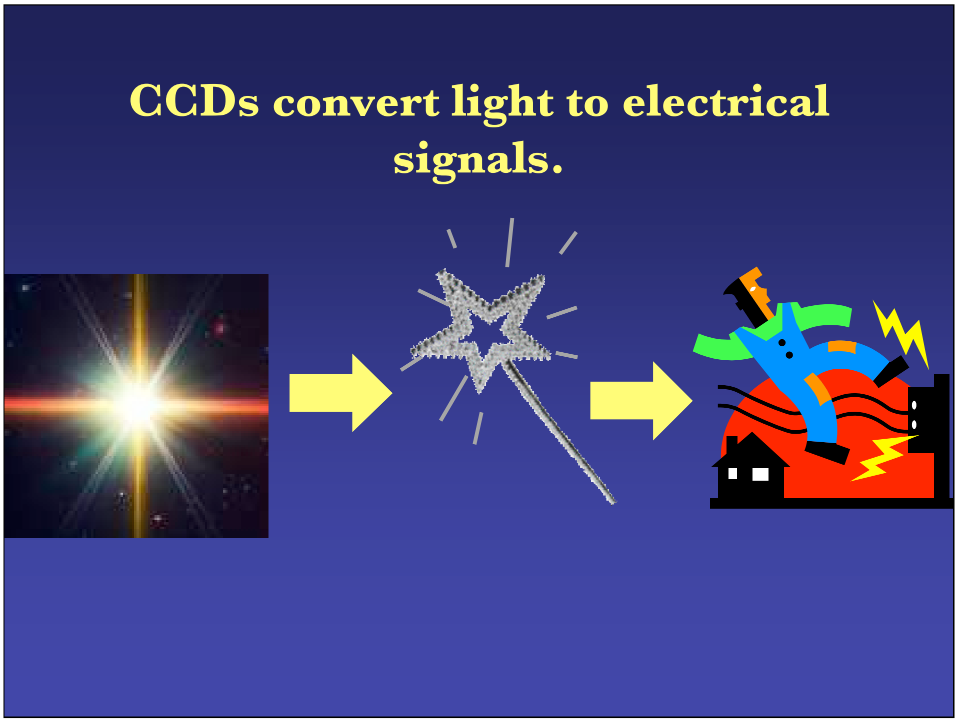
The images taken on the CCD are read onto computer disk, and can be copied to DVD, CD-ROM, data tape, or even sent over the internet to the astronomer's home computer for later analysis.

Keck I control room on the Big Island of Hawaii. Jana Pittichova, NSF-NATO Fellow, sits at the computer. The screen on the left is a videoconferencing link to the telescope 11,000 feet higher in elevation. The telescope operators, who are used to the elevation, stay up on the mountain, while the observers, who can't think clearly at altitude, remain in thick air.

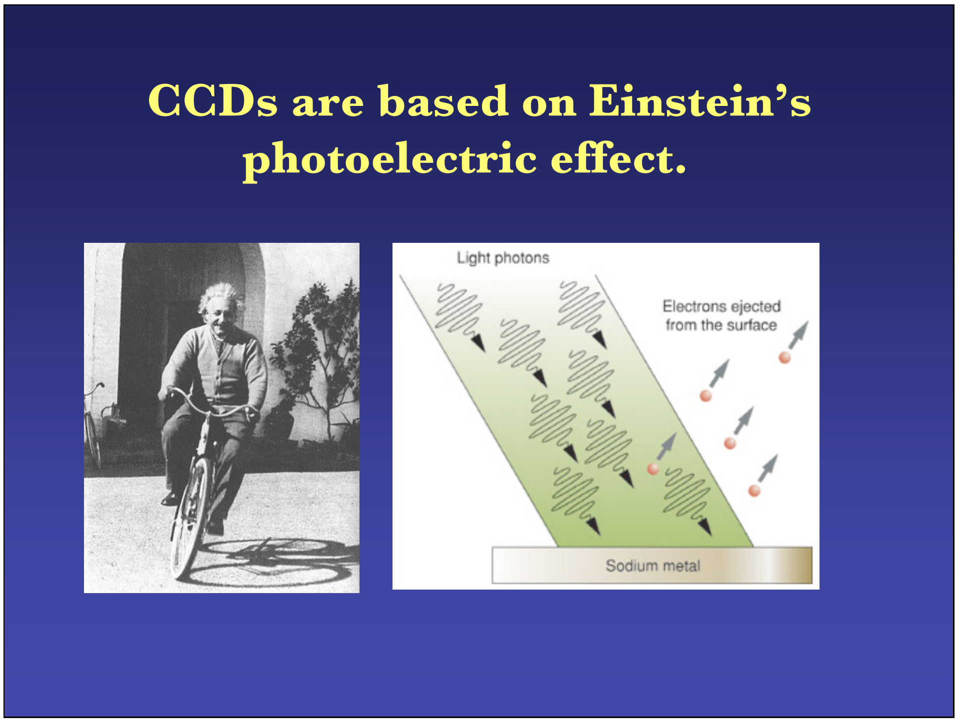


Taking long images is risky. What if, after one hour, the telescope tracking stops? The stars will quickly trail across the field, ruining the image. Or what if a meteor flashes across the field? The electricity fails? By being able to add shorter images together, you can get longer effective exposures without taking such big of risk. If you lose one 15 minute exposure, you still have a dozen others to work with.

In these images, the brightness level was adjusted so sky noise appears the same level.

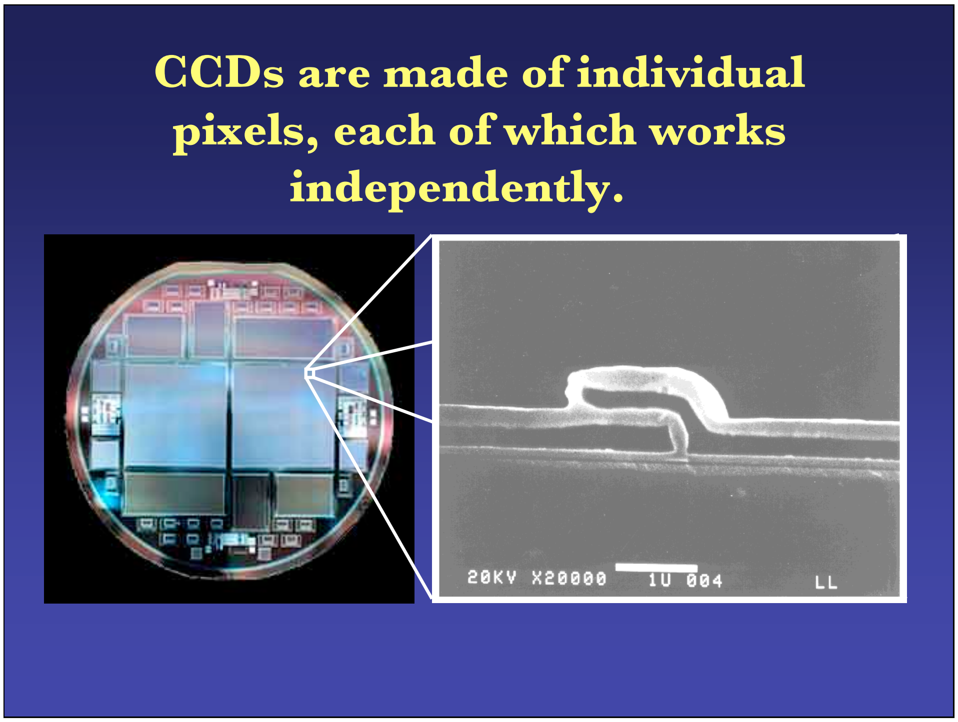


To store information on a computer disk, we need to convert the incoming light into electrical signals. CCDs are very adept at doing this, though it is not magic.



The photoelectric effect works with any atom, but was discovered with sodium. When light photons of sufficient energy hit an atom, the photon is absorbed and an electron flies off of the atom. Einstein's 1921 Nobel Prize was for explaining that this effect (which was previously known) was due to light being made of individual photons.

Silicon, used to make CCDs, releases electrons due to the photoelectric effect when hit by light of infrared and optical wavelengths. This, along with its known uses in circuitry, makes silicon the primary constituent of astronomical CCDs.

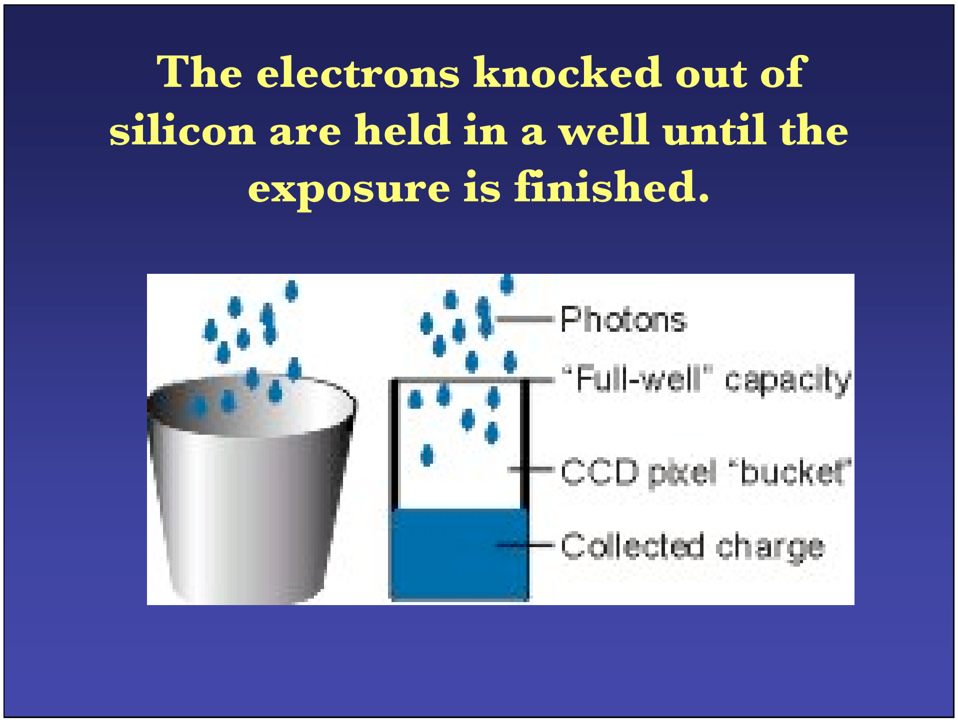


A CCD is made of millions of individual pixels ("picture element"). Most CCDs have pixel sizes of 15-30 micrometers ("microns"). With the scale of most telescopes, these pixels translate to angular scales of a tenth to one arcsecond.

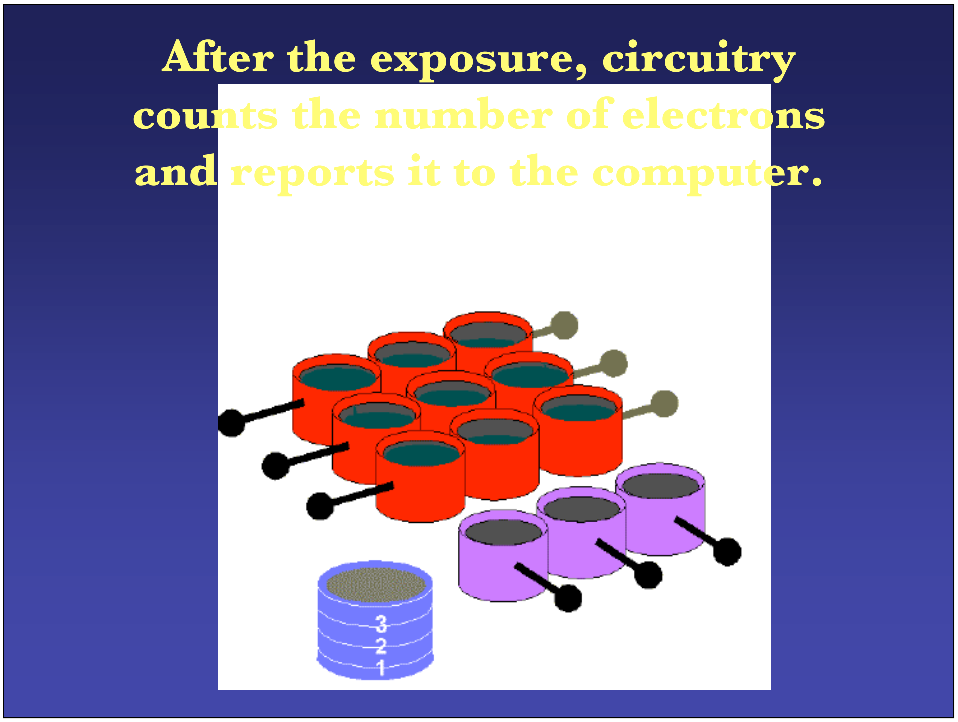
Each degree of angle has 60 arcminutes, and each arcminute is equal to sixty arcseconds, so one arcsecond is 1/3600 of a degree. An arcsecond is also the typical scale of blurring due to Earth's atmosphere. So, it doesn't make sense to have larger pixels, because that would artificially blur astronomical images. But we don't want to get too much smaller, because smaller pixels are both more expensive and require more data storage, but we don't get additional information when the pixel size is much smaller than the seeing.

Astronomers refer to CCD size by the number of pixels along each side of the CCD, like "2k by 4k" for a CCD with 2048x4096 pixels. If we multiply this out, we find that a 2kx4k CCD is equivalent to 8 megapixels. The largest commonly-used CCDs are 4k by 4k, or 16 megapixels. To get larger images, we put multiple CCDs next to each other in a mosaic-tile pattern.

The Megacam CCD camera on the MMT telescope is made of 36 2k by 4.5k CCDs, for a grand total of almost 340 million pixels!

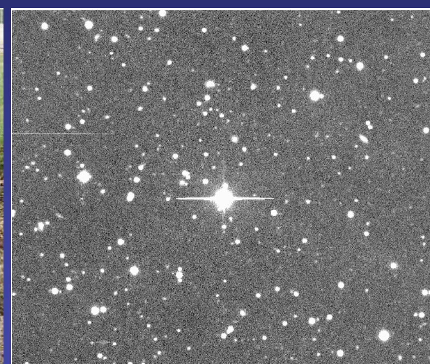


Each pixel is an individual well that can hold electrons as long as the electrical circuitry is on. Like rain being collected in a bucket, photons are collected in each pixel and held until the "rainstorm" (I.e. the exposure) is completed. At this point we can empty the buckets and determine how much rain has fallen.



The CCD readout is done by “pouring” each pixel into the readout electronics. The readout is done “serially,” meaning that each row is emptied, one pixel at a time, into the readout electronics. The number of electrons, or the number of input photons, is measured and reported to the computer. The computer takes the numbers for each pixel and assembles an image.

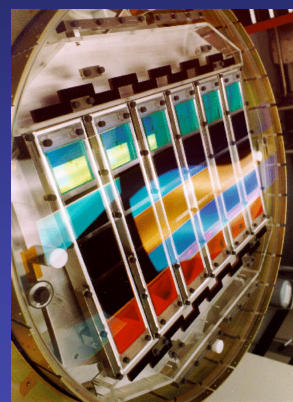
If the signal is too high, the circuitry can't count the electrons – the pixel is "saturated."



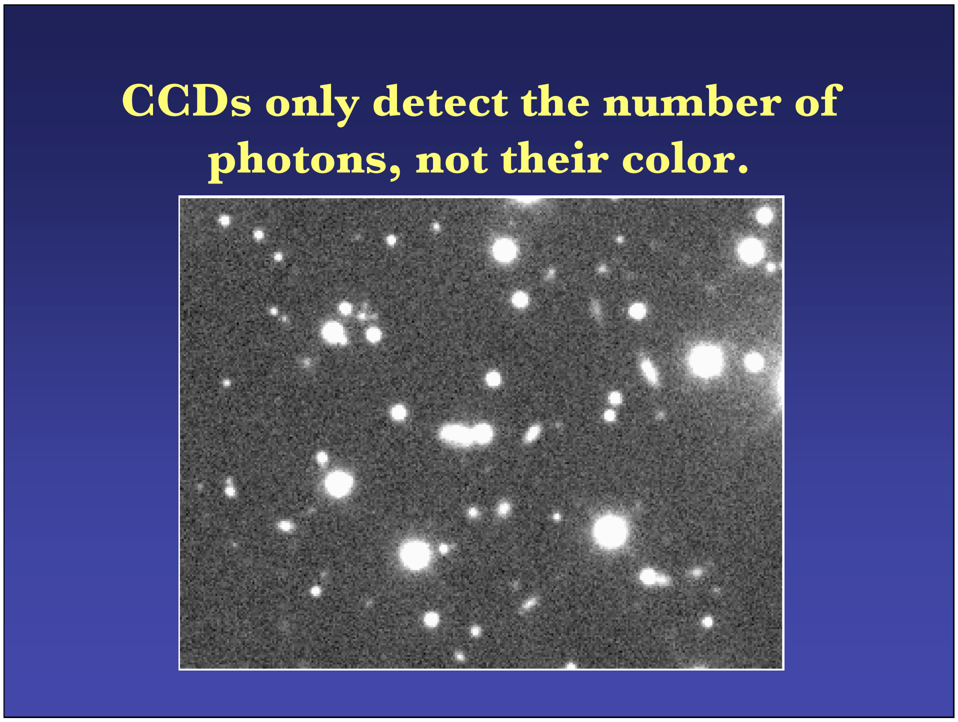
If you try to put more water in a bucket than the bucket can hold, the bucket will overflow.

If more photons hit a pixel than the pixel can hold, the electrons will spill out into neighboring pixels. The filled pixel is called sautrated. The long "rivers" of electrons are called "bleed trails."

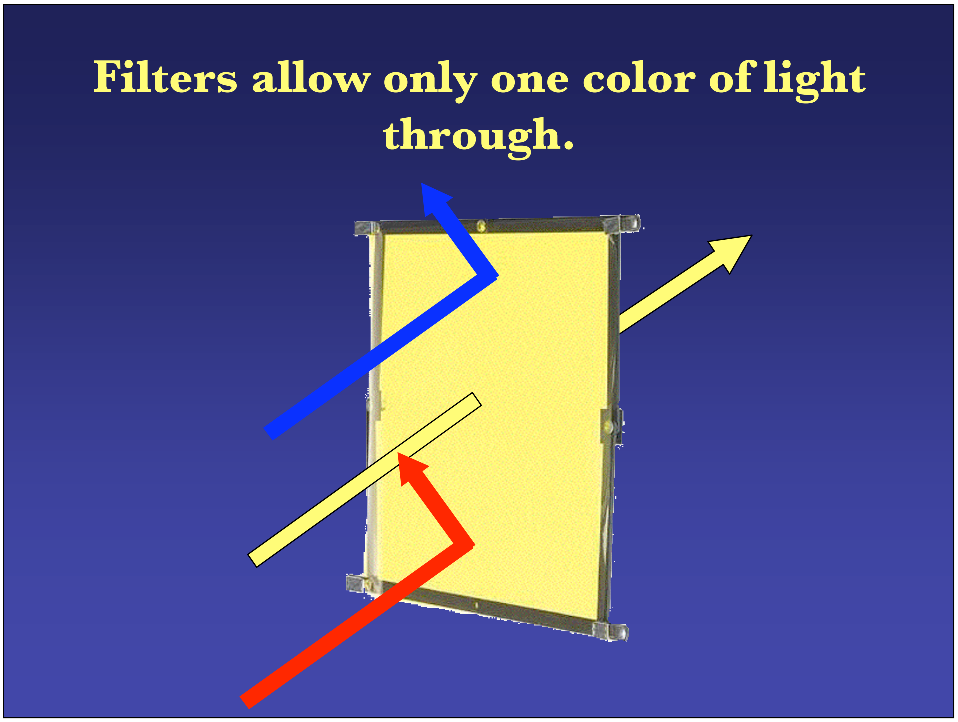
Colors are measured by taking images through colored glass filters.



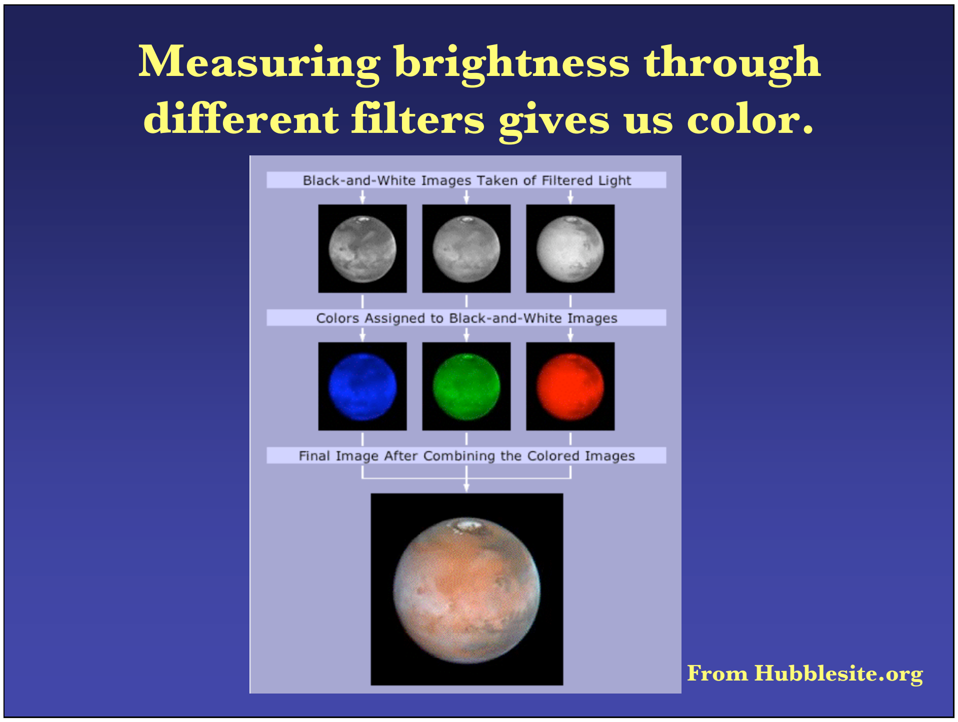
Light is made of colors. Astronomers can analyze how objects differ in color by taking pictures though different filters.



Any photon that hits a CCD gets recorded. The CCD is completely unable to tells us what color any individual photon was. So, a CCD alone is completely unable to tell us anything about the colors of stars or galaxies.

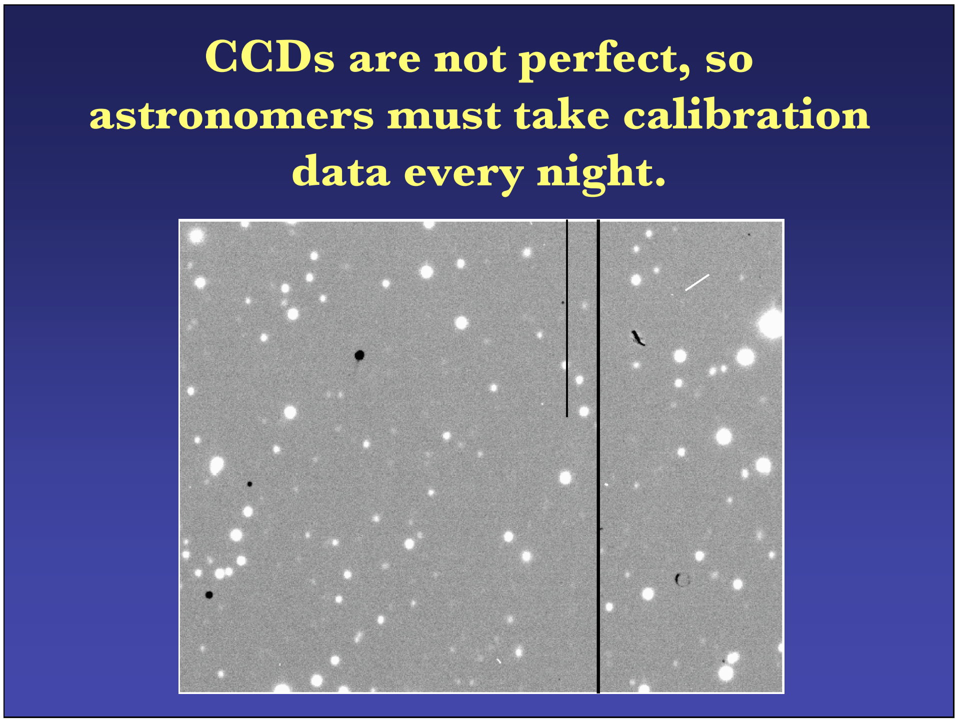


A good filter only lets one color of light through. The other colors are absorbed or reflected back from whence they came.



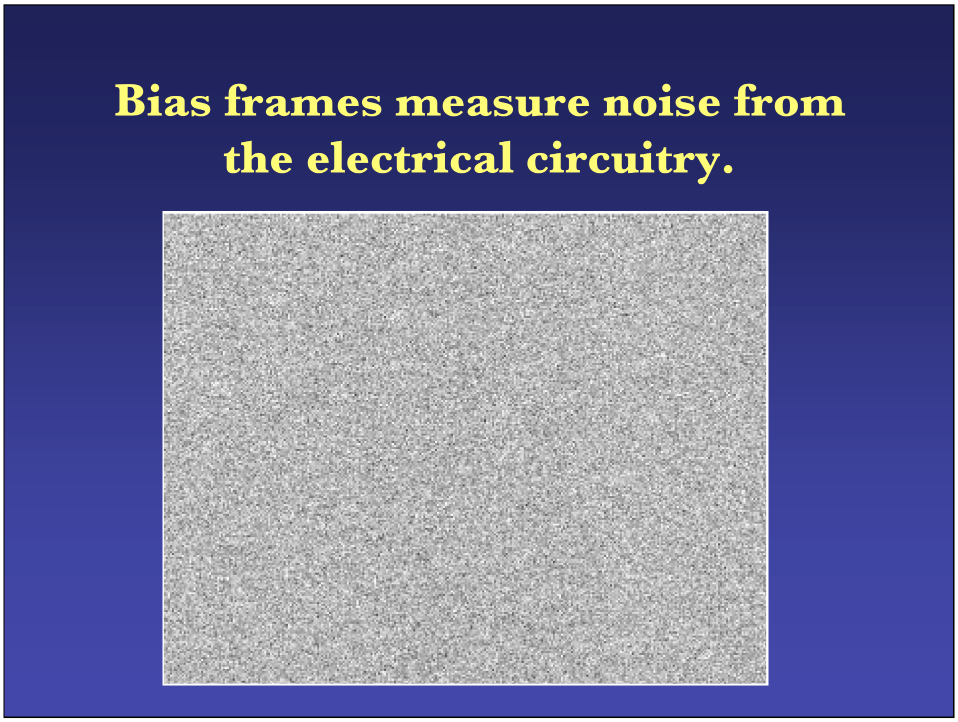
So, astronomers learn about the colors of objects by placing CCDs behind colored filters. By putting a CCD behind a blue filter, we only detect blue light. Objects that emit a lot of blue light will appear bright through a blue filter, while objects that emit little blue light won't look as bright. Objects that emit a lot of red light will appear bright through a red filter, while objects that don't emit a lot red light appear faint through a red filter.

By combining information from multiple filters, we can determine the intrinsic color of an object. If an object is bright in red, green and blue, it is intrinsically white. (Look at the top of Mars, with the white polar ice cap). If an object is bright in red, fainter in green, and dark in blue, it will appear orange, like the face of Mars above.

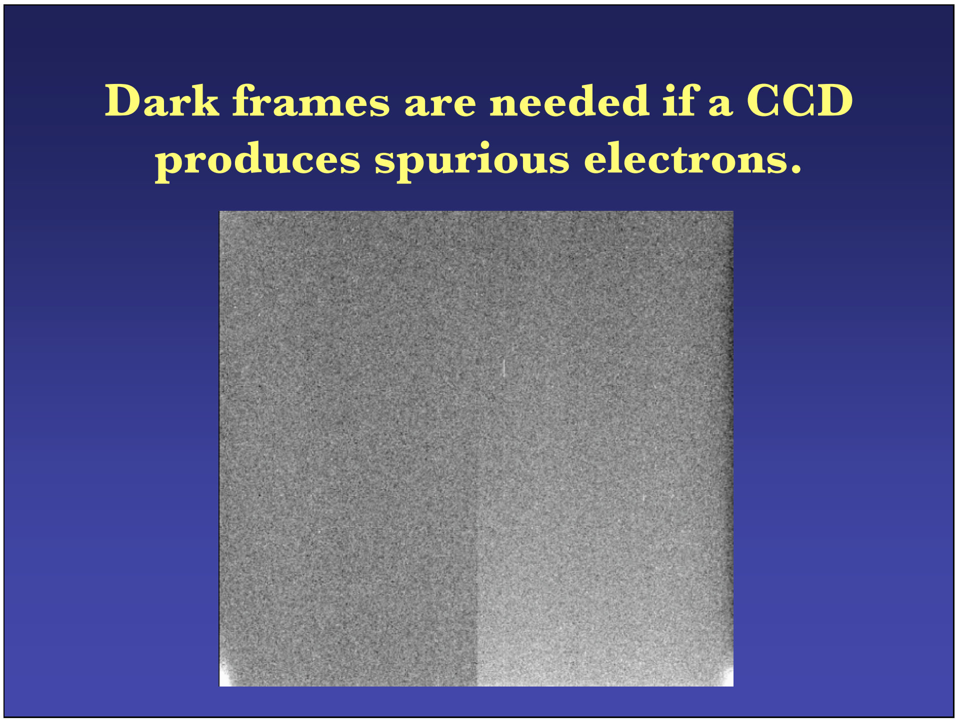


CCDs are not perfect imagers. Some pixels don't detect light as efficiently as others (like the circular and odd-shaped spots above). Some don't detect light at all (like the vertical lines above). Other times, radiation from space can mimic light (like the trail at the top right of this picture). Due to Murphy's Law, the object you are interested in will fall on top of some of these pixels.

By taking appropriate calibrations, we can correct for many of these problems.

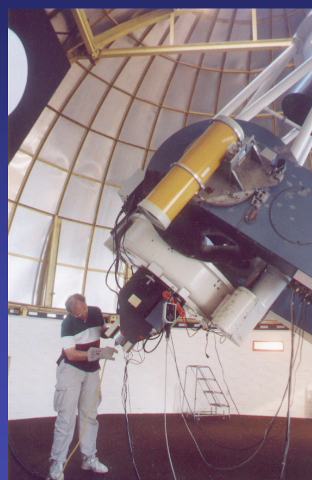


All electronics make some kinds of noise. By telling the CCD to read out without opening the shutter, just pretending like it took a picture, we can measure the noise due to electronics and remove it from our images.

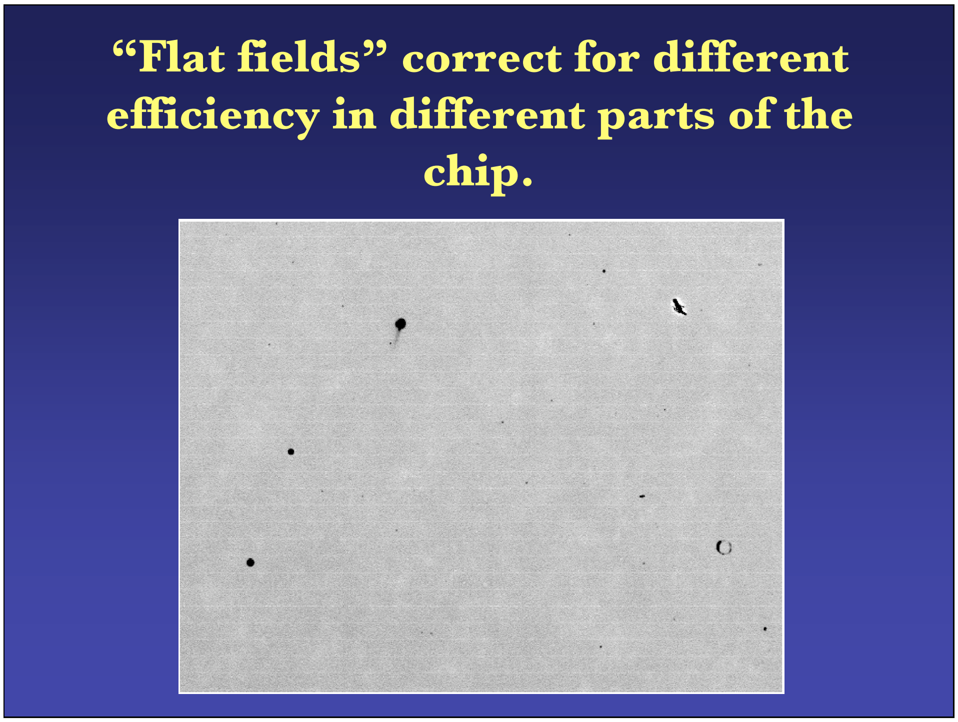


Sometimes when a CCD is just sitting there, it can produce electrons without light hitting the CCD. In the case of the CCD above, the lower corners show such light. This came from the electronics heating the corner of the chip. The dark frame is taken by exposing the CCD without opening the shutter, and then reading it out.

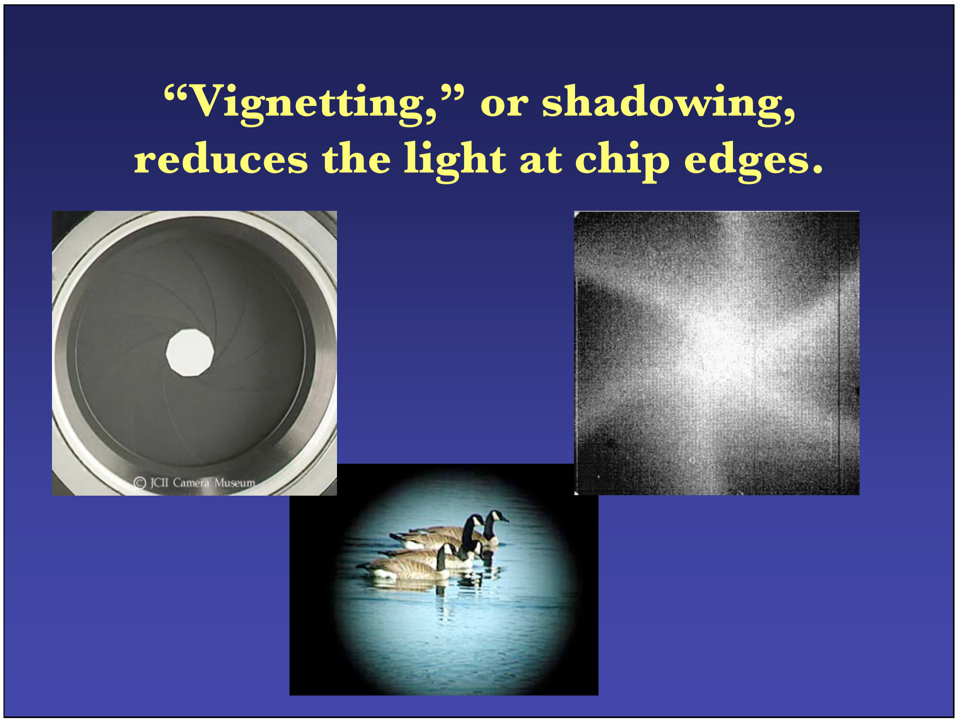
Professional astronomers rarely use these for optical light.



In the early days of CCDs, bias frames and dark frames were very important. Astronomers these days cool the electronics with liquid nitrogen, at a temperature of 77 Kelvin, or 77 degrees above absolute zero. The extreme cold keeps the noise and false detections down.

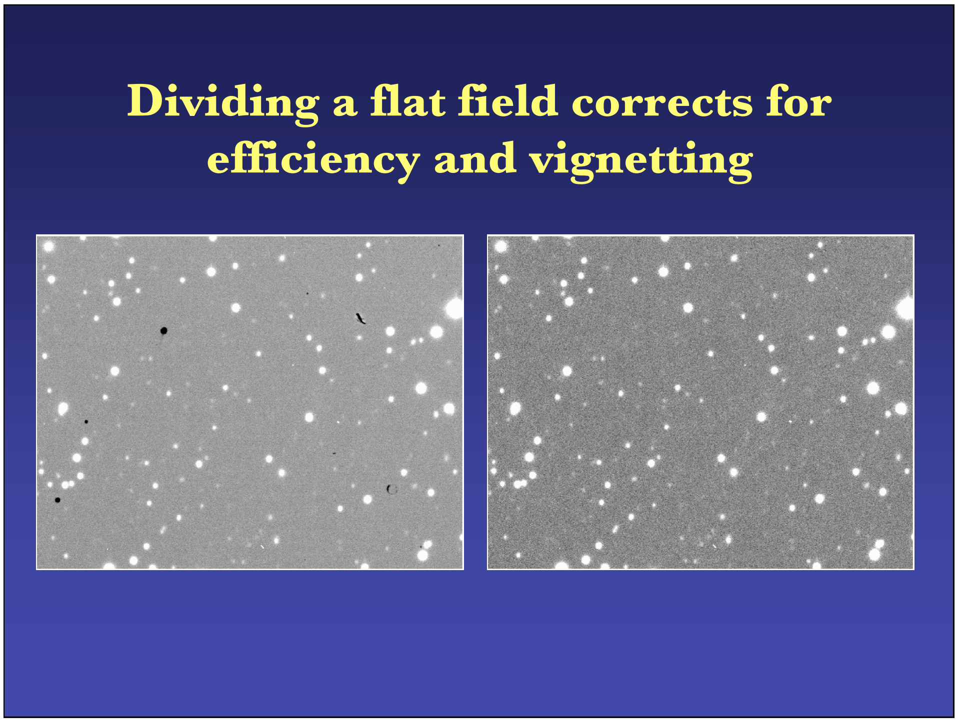


To correct for the other defects, we use a "flat field," or a picture of a blank screen or the blank sky. Every point in the image should have detected the same number of photons. So, if we detect fewer photons than that, we know how many are missing and can correct for it.



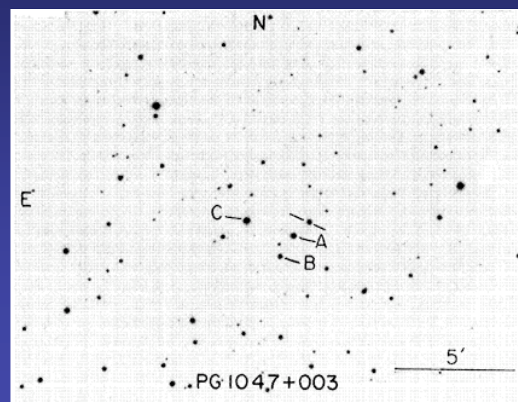
Another problem is that the edges of the chip get fewer photons than the center. That's because the center of the shutter is the first part to open, and the last part to close. The picture on the upper right shows a real picture taken with a very short exposure at a telescope -- the pattern, an "iris pattern," looks like the camera shutter on the upper left. The center picture shows an extreme version of vignetting. Vignetting is visible in many digital camera photos.

Vignetting can be taken out with flat fields in some, but not all, circumstances.



To correct with a flat field, we divide the original image by the flat field. The top left shows the original image, the top right is the corrected version. With good flat fields, the ugly spots are calibrated out and we can get useful data out.

Images of "standard stars" allow images to be put on an absolute scale.



Astronomers want to know how bright stars are in comparison to each other. We do this by the use of standard stars, which are stars that astronomers agree how bright they are.

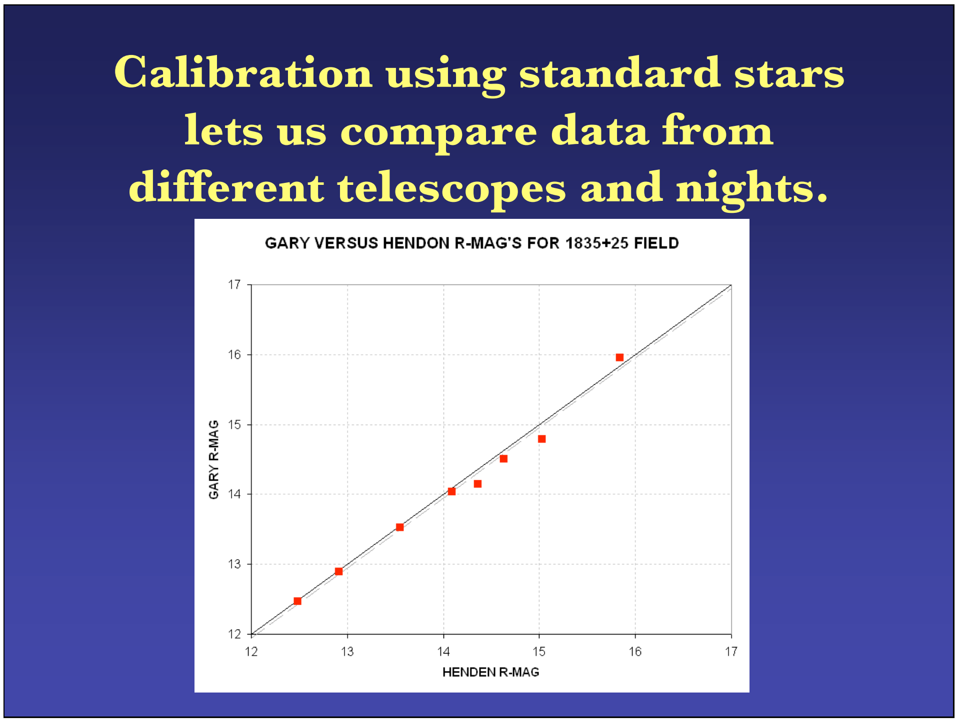
The picture on the left is the national kilogram. It is the definition of a kilogram -- all masses are a comparison to this lump of metal.

Likewise, for standard stars (an example of four is shown on the right), astronomers have agreed on how bright these are. So all other stars are measured in relation to these standards.

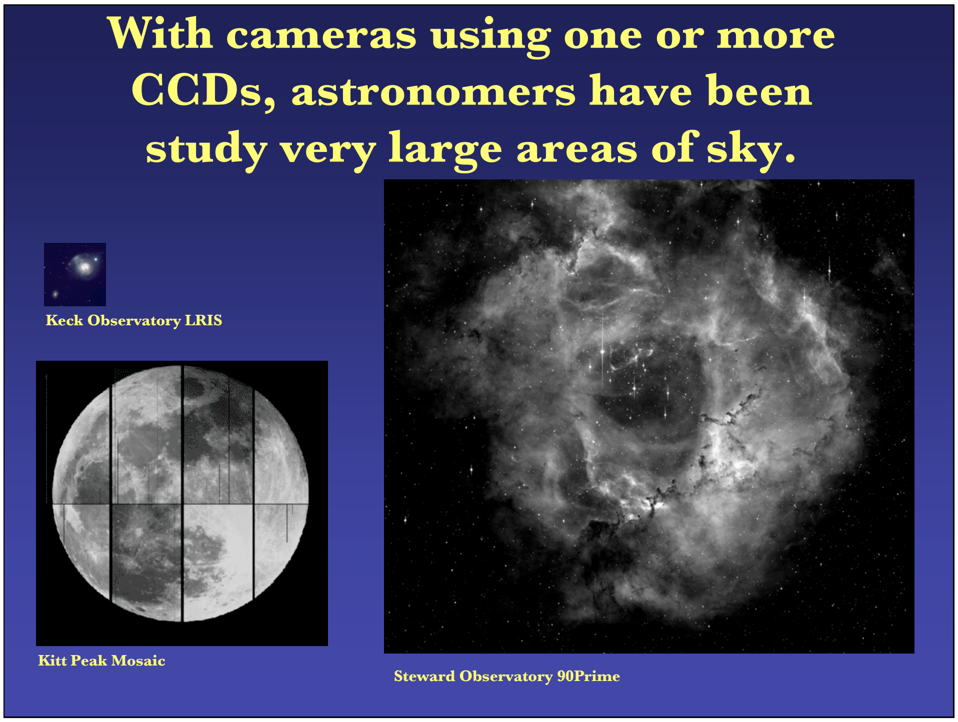
Different telescopes and instruments have different throughput.

Different sizes of telescopes and different instruments will funnel different amounts of light down to the CCD. The standard stars allow us to correct for these differences.

Our atmosphere lets different amounts of light to reach the ground. Haze and dust can block some light, and the amount is unclear. By measuring standard stars, we can correct for the unknown amount of dust.



By using standard stars, we put all of our data on the same scale. We can then compare data on the same star taken at different telescopes. This graph shows comparison of magnitudes of 8 stars taken by two different astronomers. If the points fall close to the line, then the two astronomers are agreeing.

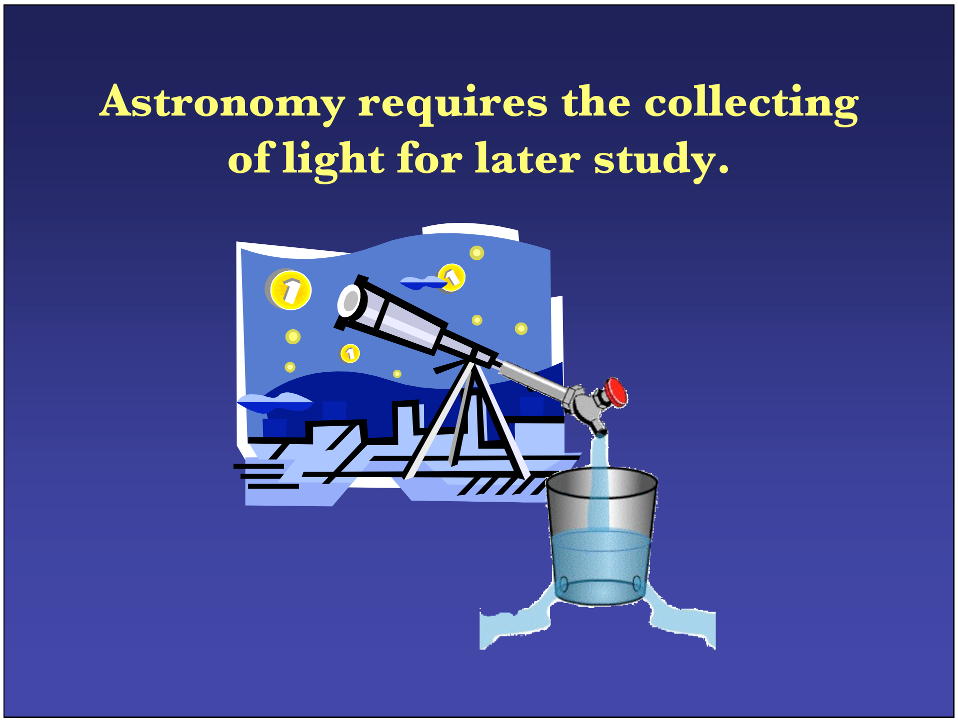


Depending on the design of the telescope and the design of the camera, different CCDs can take pictures of different areas of sky. These pictures are real CCD images put on the same scale. Some CCDs take detailed pictures of small areas, some take coarser pictures of very large areas.

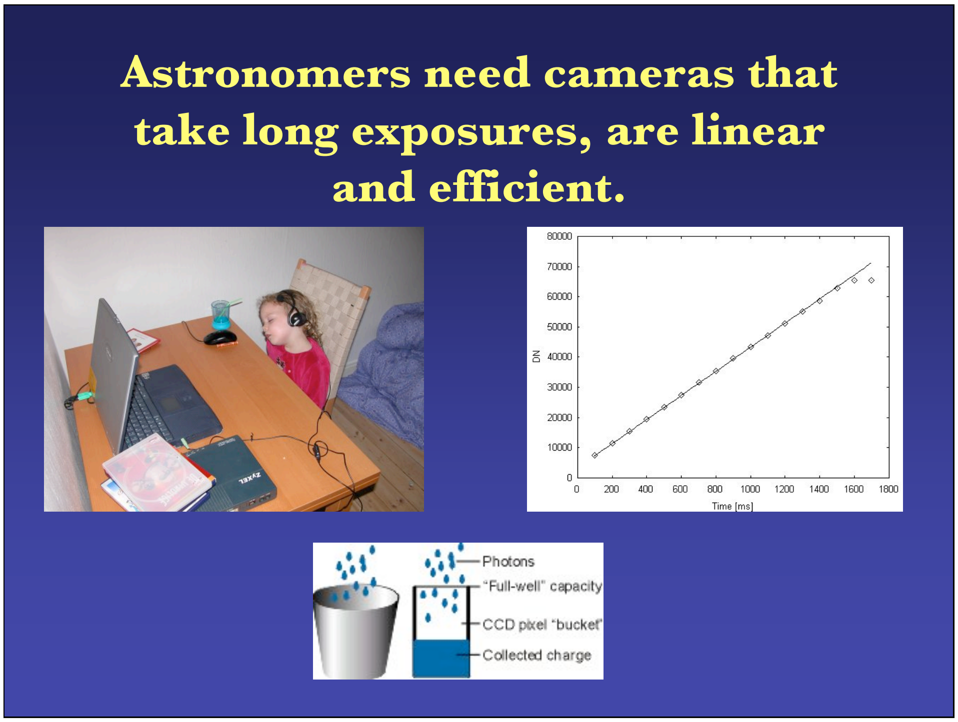
Upper left: Galaxy NGC 3656 taken at the 10-m telescope at Keck Observatory.

Lower left: The moon, taken with the 4-meter telescope at Kitt Peak National Observatory.

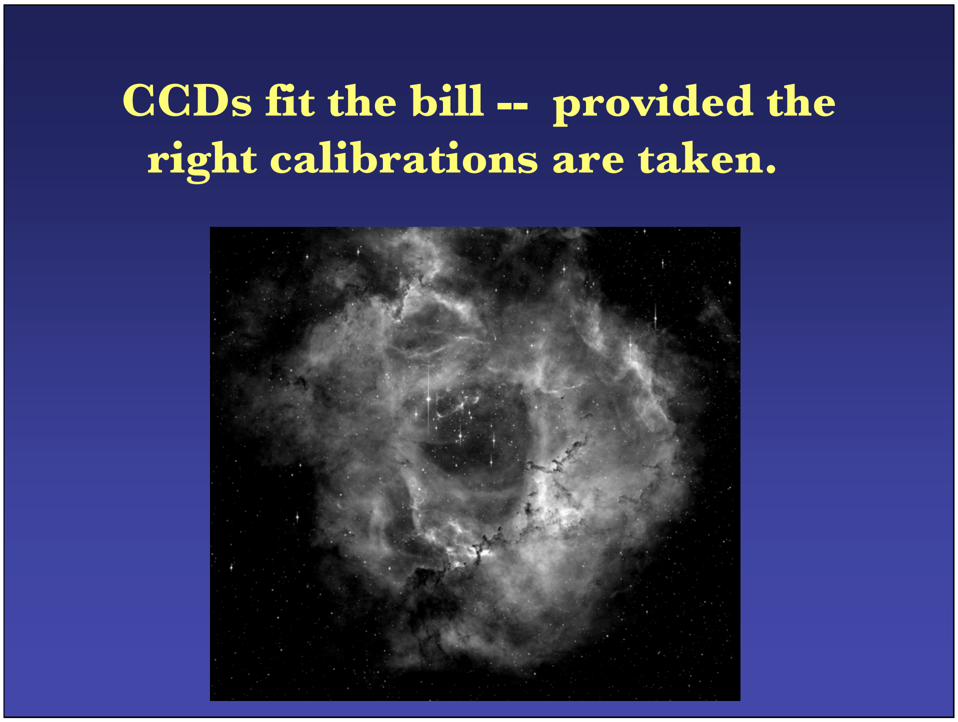
Right: The Rosette nebula, taken with the 90-inch telescope at Steward Observatory.



In summary, the goal of observing in astronomy is to collect light and save it for study back at home.



The properties that an astronomer needs in a camera are that it can take long exposures (because longer exposures let us see fainter), it is linear (doubling the incoming light doubles the reaad-out brightness), and it is efficient (meaning that almost every incoming photon is captured).



If we calibrate our data, CCDs fill all of those requirements. For this reason, almost every astronomical observation done in infrared or optical light on Earth or in space uses CCDs.

Some Useful Websites

(Not Just About CCDs)

- http://www.professor-astronomy.com
  - A website and blog describing the day-to-day life of an astronomer.
- http://www.univie.ac.at/webda/
  - A website containing data on open star clusters. Through a little poking around, you can find tabulated magnitudes so students can make their own color-magnitude diagrams. Some good clusters to look at: M67, NGC 2516, M35
- http://en.wikipedia.org/wiki/Charge-coupled_device
  - The Wikipedia entry describing charge-coupled devices.
- http://electronics.howstuffworks.com/digital-camera.htm
  - An article describing how digital cameras work, which are similar to charge-coupled devices.