News

• Lab time assignments are on class webpage.
• Lab 2
  – Due September 24.
• Lab 3
  – Observing starts tomorrow evening. Show up whether cloudy or clear.
  – Due October 8.
Other Telescope Properties

• **Field of View:** The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  
  – Fundamental limit is usually off-axis image aberrations.
  
  – Size of the eyepiece or detector is also important.
Off-Axis Aberrations

• Coma: rays striking different zones focus at different locations and distances.
Off-Axis Aberrations

- Astigmatism: off-axis rays striking different planes focus at different distances.
Ritchey-Chretien Telescopes

• Have hyperbolic surfaces on the primary and secondary. Additional surface allows a reduction in aberrations.
  – Particularly reduce coma, which causes asymmetric images, relative to astigmatism, which does not.
    • Images better suited for measuring positions – astrometry.
  – Do have \textit{field curvature} (a curved focal plane).
• Most large professional telescopes use the R-C design.
Off-Axis Aberrations

• Vignetting: not all off-axis rays make it to the focal plane – generally hit baffles or stops.
Light enters Hubble's aperture and travels down the main baffle. A baffle is a surface which eliminates stray light.

Light is reflected by the primary mirror which measures about 8 feet (2.4 meters) in diameter. Because of the concave shape, the primary mirror converges the light to the secondary mirror through a secondary baffle.

The secondary mirror, measuring about 1 foot (0.3 m) in diameter receives the light. It in turn reflects the still-converging light back toward the primary mirror through a central baffle.

The light travels through the primary mirror, to reach the focal plane, where the science instruments examine the light.
Schmidt telescope designs use a spherical primary mirror to get a wide field of view, but suffer from spherical aberration – which must be corrected.
THE FOVR FOOT SCHMIDT PHOTOGRAPHIC TELESCOPE

5 degree fov
Other Telescope Properties

• Field of View: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  – Usually determined by off-axis image aberrations.
  • 0.5 degrees for our telescope’s Ritchey-Chretien optics

– Other limits:
  • Baffles inserted to eliminate scattered light.
Other Telescope Properties

- **Field of View**: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  - Usually determined by off-axis image aberrations.
    - 0.5 degrees for our telescope’s Ritchey-Chretien optics
  - Other limits:
    - Baffles inserted to eliminate scattered light.
    - Size of the detector (the cameras on our telescope and on the Hubble Space Telescope).
HST focal plane is about 0.5 degree across. But the individual cameras cover only a small fraction of it.
FOV of the Kepler space telescope: about 10 degrees across. Is an 0.95m diameter telescope.

Detector pixels are so large on the sky that defocus the telescope so that stars are sampled by a few pixels.
Large Synoptic Survey Telescope (LSST): 8.4 m primary mirror; the 3-mirror design gives a 3.5° fov. In operation late in this decade (maybe).
Other Telescope Properties

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  – Usually determined by off-axis image aberrations.
    • 0.5 degrees for our telescope’s Ritchey-Chretien optics
  – Other limits:
    • Baffles inserted to eliminate scattered light.
    • Size of the detector (the cameras on our telescope and on the Hubble Space Telescope).
  – With an eyepiece: (apparent eyepiece fov)/mag
    • For most of our eyepieces apparent fov = 70 degrees.
CCD Imaging Detectors

• Charge Coupled Device: convert photons of light to electric charges.
  – Manipulation and detection of electric charges is well advanced (electronics).
  – Signals easily digitized for analysis by computers.

• Detector of choice in the near infrared, visible, and ultraviolet regions of the electromagnetic spectrum.
  – Have good quantum efficiency (50 – 80%), excellent linearity, and large dynamic range (~20,000)
SBIG STL1100m CCD Camera

- Contains two CCDs
  - 4008 x 2672 pixels main imager
  - 680 x 500 pixels guide imager
Focusing the CCD

• We focus the telescope on the CCD by moving the secondary mirror.
  – Controls are on the observing panel.
  – Mirror position is shown on the display above the panel (turn on with the green power button).
  • Don’t push the yellow “zero” button.
Focusing the CCD camera is done by moving the position of the secondary mirror with these controls.

The position of the secondary is shown by this readout. Turn it on with the green button. Do NOT push the yellow button.

Focusing the CCD camera is done by moving the position of the secondary mirror with these controls.
Focusing the CCD

• We focus the telescope on the CCD by moving the secondary mirror.
  – Controls are on the observing panel.
  – Mirror position is shown on the display above the panel (turn on with the green power button).
    • Don’t push the yellow “zero” button.
  – Be careful not to use saturated images to determine the focus.
  – Best focus will be around 1.500 mm, value increases by about 0.100 mm for every 5 C decrease in temperature.
Focusing the CCD

• Use RUPhAst and its aperture photometry tool (p key or left-mouse-button) to measure the full-width at half-maximum (FWHM) of stellar images.
  – RUPhAst fits a gaussian to the profile of the star to determine the FWHM.
  – Smallest FWHM is the best focus.
    • But should also visually assess the quality of the fit to the profile.
    • Subsequent slides show a good and a bad focus that had similar derived FWHM’s.
SBIG STL1100m CCD Camera

• Contains two CCDs
  • 4008 x 2672 pixels main imager
  • 680 x 500 pixels guide imager
Same field in *The Sky*.

Rotation tool (in Orientation menu)
Main CCD field of view

Guide CCD field of view; When the telescope is pointing west of the meridian, the position angle of the guide CCD is 270°.
When the telescope is pointing east of the meridian, the position angle of the guide CCD is 90°.
TrES-3 b

A 10th magnitude star that would be a good guide star.
Offsetting the telescope east and south puts the guide star in the guider.
Guider Setup

Usually have the main imager selected in *Take Image* tab.
However, can select Autoguider to choose binning (1×1) and reduction (autodark subtract).
Guider Setup

Set up guiding with the Autoguide tab. Note can guide using either the guide CCD or the main CCD.

Choose exposure for guiding.

Take an image with the selected guider.

Start guiding

Calibrate guider (this sometimes helps if the guiding is poor)
• Select the Autoguide tab and take a test exposure of a few seconds.

• Click in the displayed image to select a guide star. White box flashes and coordinates appear in the tab.

• Start guiding with Autoguide button (will hear clicks of corrections being made).

Figure 2: An autoguide image taken for reference. Note that there is one star significantly brighter than the others; this is a good choice for a guide star.
Over-correcting by the guider can cause the telescope to oscillate back and forth. These images can still be useful if use a big aperture.
Really bad guiding. Waiting a few correction cycles for the guiding to settle down before starting an exposure can help. If the problem persists, try doing a guider calibration.
RAIN (PHOTONS)

BUCKETS (PIXELS)

VERTICAL CONVEYOR BELTS (CCD COLUMNS)

HORIZONTAL CONVEYOR BELT (SERIAL REGISTER)

MEASURING CYLINDER (OUTPUT AMPLIFIER)

CCD Analogy

Slides from Simon Tulloch
Exposure finished, buckets now contain samples of rain.
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder.
After each bucket has been measured, the measuring cylinder is emptied, ready for the next bucket load.
A new set of empty buckets is set up on the horizontal conveyor and the process is repeated.
Eventually all the buckets have been measured, the CCD has been read out.
CCD Calibration

• Bias Level: the response of the electronics when no signal is present.
  – Determined with a *bias image*: no light, exposure time = 0; subtracted from the science image.
  – Can vary with position, which is reason for subtracting an image.

• Dark Current: rate of thermal emission
  – Determined by a *dark image*: no light, exposure time ≠ 0; subtracted from science image.
  – Also can vary with position. Hot pixels have high dark current.
Bias image from our camera (dark images are similar).

Note the top-to-bottom gradient. Is actually dark current.
Zoomed bias frame from our camera.

Note the “hot” pixels with high dark current. One in the image is so “hot” that it is producing a hot column.
CCD Calibration

• Because of the strange features of the bias images in our camera, we usually just take one or more dark images with an exposure time equal to the science image.
  – Subtract the dark from the science image to remove both the bias level and the dark signal.
  – The CCDSOFT system has a mode that automatically takes a dark image after the science image and subtracts it.
CCD Calibration

• Sensitivity variation: pixel-to-pixel variation in the quantum efficiency.
  – Correct for this by taking a uniformly-illuminated “flat-field” image (the inside of dome or the twilight sky). Divide the science images by a normalized flat-field image.
  – Our camera also does not completely illuminate the corners of the CCD (vignetting). This is also corrected with the flat.
The “doughnuts” are the out-of-focus shadows of dust on the filter or CCD window. The corners are darker because of incomplete illumination (vignetting).
Contours of a flat-field image divided by maximum.

So only in the right-hand corners is the illumination less than 90% of maximum.
Horizontal and vertical cuts through a normalized flat.

Note that pixel-to-pixel sensitivity variations are less than 1.5%.
CCD Calibration

• Gain: the number of electrons per A-to-D digital unit (or data number).
  – Really an inverse gain (is small if the amplifier gain is large).

• Read noise: the noise added by the amplification and measurement (usually given in electrons).
Zoomed bias frame from our camera.

Again note hot pixels. “Speckling” around the constant bias level is due to read noise.
The “speckling” is a combination of pixel-to-pixel sensitivity variations and the Poisson noise of the photon arrivals.
Differencing two images reduces the effect of signal variations (due to variations in brightness or pixel-to-pixel sensitivity variations) on the measured variance around the mean.

Use IDL to do image arithmetic and display the result with PhAst.
Standard deviation of the pixel values in the difference of two biases.
Standard deviation of the pixel values in the difference of two flats.
CCD Calibration

• Read noise: the noise in electrons added by the amplification.

  – Difference two bias images:

    • \( \Delta = s_2 - s_1 \)
    • \( \Rightarrow \sigma_\Delta^2 = ((d\Delta/ds_1)\sigma_{s_1})^2 + ((d\Delta/ds_2)\sigma_{s_2})^2 = \sigma_{s_1}^2 + \sigma_{s_2}^2 \) from propagation of errors

    • Since the noise in each pixel of a bias frame is the same read noise, \( \sigma_{s_1} = \sigma_{s_2} = rn \) and \( rn = \sigma_\Delta/\sqrt{2} \).

    • So just need to find the variance of \( \Delta \) around mean for patches of the difference between two bias frames.

  – Produces the read noise in \( \text{du} \).
CCD Calibration

• Read noise: the noise in electrons added by the amplification.

• Gain: the number of electrons per A-to-D digital unit (or data number).
  – Determined by the noise in an image with high signal: is dominated by Poisson noise (shot noise), \( \sigma_{Ne} = \sqrt{N_e} \).
  – Again difference two flat field images to remove variations due to illumination and sensitivity variations.
CCD Calibration

- Gain: the number of electrons per A-to-D digital unit (or data number).
  - $\Delta = s_2 - s_1$ and $s = (s_2 + s_1)/2$
  - $\Rightarrow \sigma^2_{\Delta} = \sigma^2_{s_1} + \sigma^2_{s_2} = 2\sigma_s^2$
  - Now $N_e = g \times s \Rightarrow \sigma_{N_e} = g \times \sigma_s$ from prop. of errors and $\sigma_{N_e} = \sqrt{N_e} = \sqrt{g \times s}$.
  - So $\sqrt{g \times s} = g \times \sigma_s \Rightarrow g \times s = g^2 \times \sigma_s^2 = g^2 \times \sigma_{\Delta}^2 / 2$
  
  - Solving for $g$: $g = 2s / \sigma_{\Delta}^2 = (s_1 + s_2) / \sigma_{\Delta}^2$
**CCD’s: Creation of Charge**

- A brief review of electron states in solids

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**Energy of electrons**

- **Conduction Band**
- **Valence Band**

**Fermi level in gap.**

- **Insulator**
- **Semiconductor**
- **Conductor**

**The large energy gap between the valence and conduction bands in an insulator says that at ordinary temperatures, no electrons can reach the conduction band.**

**In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.**
CCD’s: Creation of Charge

- Photoelectric effect
  - Silicon bandgap is $E_g = 1.11$ eV. Corresponds to
    - $\lambda = \frac{hc}{E_g} = 1.12 \, \mu m$
    - $T = \frac{E_g}{k} = 1.29 \times 10^4 \, K$
  - The rate of thermal creation of hole/electron pairs is
    $\propto \exp(-E_g / kT)$
  - The exponential is small at room temperature, but there are many electrons in a solid. So cooling is usually needed to suppress the thermal creation (“dark current”).
  - Without an electric field to separate the electron-hole pairs, they recombine in $\sim 100$ microseconds.
Photoelectric effect in silicon

- Probability that a photon is absorbed when traversing an interval $dx$ of Si is $dx/a(\lambda)$, where $a(\lambda)$ is the absorption length.

$$d\text{Flux} = -\text{Flux} \frac{dx}{a(\lambda)}$$

$$\Rightarrow \frac{dF}{F} = -\frac{dx}{a(\lambda)}$$

$$\Rightarrow F(x) = F_0 \exp\left(-\frac{x}{a(\lambda)}\right)$$

- Prob a photon absorbed in $x$ is $(1-R)(1-\exp(-x/a(\lambda)))$

where $R$ is the reflection coeff.
CCD’s: Charge Storage (pixel)

- The basic CCD element (pixel) is the metal-oxide-semiconductor (MOS) capacitor.
  - Applying positive voltage to the metal electrode (gate) repels holes, producing a depletion region with an E field in it.
  - Photoelectrons collect in the depletion region.

Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.
Charge collection in a CCD

Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create ‘charge packets’. Each packet corresponds to one pixel.
Charge Collection: Full Well

• As charge packets become larger, the electrons repel each other and the charge leaks into adjacent pixels.
  – Usually along a column; channel stops prevent diffusion between columns.
  – Bigger pixels (area and depth) have larger full wells.
  – Values: 30,000 – 500,000 electrons. Our camera has a full well of ~60,000 electrons.
Below the image area (the area containing the horizontal electrodes) is the ‘Serial register’. This also consists of a group of small surface electrodes. There are three electrodes for every column of the image area. Once again every third electrode is in the serial register are connected together.
Photosites have low dark current, while transfer sites have a much higher one. But transfer sites are scrubbed during exposure.
CCD’s: Charge Detection

• The crucial step is the on-chip amplifier – it must add as little noise as possible to the small measured signals.
  – Serial register dumps the charge on a capacitor and the resulting voltage is amplified.
  – There is usually more amplification off of the chip.

• Voltage is then digitized (with 12 to 16 bits).
  – Must add an offset voltage (“the bias”)
    • The bias ensures that the input voltage to the analog-to-digital (A-to-D) converter never goes below the zero level.
The serial register is bent double to move the output amplifier away from the edge of the chip. This useful if the CCD is to be used as part of a mosaic. The arrows indicate how charge is transferred through the device.
Charge Detection Variants

• On-chip binning (e.g., 2×2):
  – Combine two or more pixels from each column in the serial register.
  – Combine two or more pixels from the serial register in the summing well.
  – Combination occurs before measurement, so no noise is added. Increases signal relative to noise and reduces readout time.

• Partial readout (half frame, quarter frame):
  – Only measure some of the pixels. Reduces readout time.