ASTR 303 Astrophysical Techniques
Final Exam
Fall 2018

You may consult any resources available. You may even work collaboratively. However, if you do work together, <u>you must take care to submit independent responses</u>.

For all questions requiring a written explanation, be as succinct as possible. Feel free to draw diagrams as well. Answer only the question asked ***in no more than about 5 sentences.*** *In most cases, 1-2 sentences will suffice. (I do not want essays!) Consult me for clarification if necessary.*

Since you have ample time, please edit your responses and write or type them neatly. On calculations you must show your work for full credit.

Your exam papers are due at 10 AM on Tuesday, December 18. Late papers will incur deductions.

1. a) What is the mechanism for the emission that we observed from the Milky Way disk at the 40-ft telescope at Green Bank?

   b) Describe the method by which you measured the spectrum of the Milky Way disk emission at the 40-ft telescope at Green Bank. Describe the processes in the telescope and instruments that led to the recorded signals, not a step-by-step list of the procedure used to acquire the data.

   c) Sketch one of the Milky Way spectra you took and label both axes. For the x-axis, label both observed frequencies and the radial velocities (at reasonable intervals) with numbers corresponding to your observations.

2. a) What is the advantage of using a semiconductor for light detection over using an insulator or conductor?

   b) The band gap of silicon is 1.12 eV. Calculate the cutoff wavelength and use this to explain why silicon intrinsic semiconductors are not useful as infrared detectors.

   c) Draw and label a diagram of a MOS capacitor and describe its use in a CCD.

   d) For a three-phase readout as described in Chapter 8, what will be the readout time for a 2048 x 2048 pixel array with a clock rate of 10 MHz? HINT: Assume 3 cycles per pixel shift and include both the parallel and serial transfer.

   e) Imagine a CCD with an amplifier at one corner of the chip and a charge transfer efficiency (CTE) of “three nines”, 0.999. What fraction of the charge stored in the pixel most distant from the amplifier actually reaches the amplifier if the array is 2048 x 2048 pixels?

3. a) Describe one way in which one can:
   i) improve quantum efficiency
   ii) reduce dark current
   of a CCD.

b) What is the source of <u>and</u> method of correcting for:
   i) bias
   ii) dark current
   in a CCD image?

c) For fast readout commercial CCDs, such as those used in smart phone cameras, the read noise can be quite high, compared to research-grade detectors. Why is this trade-off acceptable? (HINT: Consider the CCD equation for SNR from Chapter 9.)

4. Imagine that a star is known to produce 45 electrons/sec for a particular telescope-detector combination (<u>after all image processing</u>). The CCD used has a read noise of ρ^2=4 electrons/pix, and a dark current of 2 electrons/sec/pix.

Calculate the SNR for a 25 second exposure under the following situations:

a) dark sky and good seeing: sky brightness = 1.4 electrons/sec/pix, digital aperture = 9 pixels total (i.e. 3 pix on a side)
b) moonlit sky and poor seeing: sky brightness = 4 electrons/sec/pix, digital aperture = 25 pixels total (i.e. 5 pix on a side)
c) Comment on which noise term dominates in each case

5. For the observation described in **part (a)** of the previous question, imagine that you are looking at the digital image, <u>before any processing</u>, displayed as counts (i.e. number of ADU) in each pixel.

a) What is contributing to the counts in each pixel?
b) If the gain of the CCD amplifier is 5 electrons per ADU, what would be the number of ADU in each pixel on the star <u>before any processing</u>?
c) Calculate the uncertainty in your answer to part b) using Poisson statistics.

6. Imagine that we measure a standard star with known magnitude V=8.3 and color B-V=0.5 at two different airmasses, X= 1.2 and X=1.5 at which the instrumental magnitudes of the standard star, were found to be 8.56 and 8.57, respectively.

a) What is the extinction coefficient and the extinction-corrected instrumental magnitude, m_i of this star?

For a second star with V=6.3 and B-V = 0.3, we find an extinction-corrected instrumental magnitude, m_i =6.7.

b) What is the zero point and color term for the V magnitude on the standard system?

c) If I measure a third star with B-V=0.1 to have an instrumental magnitude of 10.3 at airmass X=1.1, use your answers for a) and b) to find its extinction corrected instrumental magnitude m_i and its standard magnitude in this system, V.

7. For a telescope and spectrograph with a projected slit width of 20 μm and a linear dispersion of 25 nm/mm operating in the visible range (λ = 400-700 nm), operating in the 10th order, calculate the

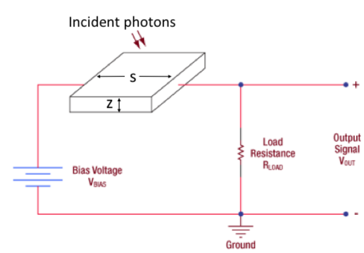
a) spectral purity, $\delta\lambda$ (HINT: watch your units!)
b) resolving power, R
c) free spectral range, $\Delta\lambda_{FSR}$
d) If I want to observe the Balmer series lines from Hα (λ=656 nm) to Hδ (λ=410 nm), how can I achieve this, given the answer to c)?

8. Imagine a silicon photoconductor device with the following properties:

charge mobility $\mu = 10^{-4}$ m^2/V/s
carrier lifetime $\tau = 10^{-6}$ s
quantum efficiency $\eta = 0.8$
electrode separation s = 10 nm

operating with a bias voltage of 10 V, detecting a source with an incident flux of 100 photons/sec.

a) Calculate the photocurrent in electrons/sec.
b) If the reflectivity of the photoconductor is 10%, what is the fraction of photons that must be not only transmitted (i.e. not reflected) but also <u>absorbed</u> in the material for quantum efficiency quoted above?
c) Given your answer to b), what must the vertical thickness of the silicon be? Use $I(z)=I(z=0)e^{-\alpha z}$ where I is the intensity of a photon beam at depth z, and $\alpha = 10^4$ m^{-1}



9. Compute the dark current for a silicon CCD (E_G=1.12 eV) operated
(a) at 300 K and
(b) at 233 K.

10. Calculate a reasonable gain factor for a CCD with
(a) a full well capacity of 300,000 electrons and a 16-bit analog-to-digital converter. (16 bits leads to possible digital values between 0 and 2^{16}-1.)
(b) a full well capacity of 100,000 electrons and an 8-bit analog-to-digital converter.

Bonus (up to 10 points): Based on your experience this semester, suggest an observing project to a student who takes this course next year. Give a specific choice of targets and justify that choice. Give that student some guidance on an observing strategy in terms of numbers of nights of observing necessary, approximate exposure times, and calibration frames to obtain. The proposed project may be similar in nature to the project you or a classmate did this semester, but you must choose a new target.

Constants and conversions
c=2.9979 x 10^8 m/s
h=6.626 x 10^{-34} m^2 kg/s
k=8.617 x 10^{-5} eV/K
1 eV = 1.602 x 10^{-19} J

Equation list

$$E = \frac{hc}{\lambda}$$

Photometry
Extinction correction
m(X) = m(X=0) + kX where
k = the extinction coefficient
X = airmass
m(X) = the instrumental magnitude at airmass X
m(X=0) = the instrumental magnitude X=0 (i.e. the extinction-corrected instrumental magnitude)

Transformation to standard system
m_i-m_{std} = ζ + εC_{std} where
m_i = the extinction-corrected instrumental magnitude (=m(X=0) from the equation above)
m_{std} = the magnitude on the standard system
ζ = the zero point of the standard magnitude system
ε = the color term for the standard magnitude system
C_{std} = the color of the star in the standard system

Photocurrent
$I = s^{-2} q \mu \eta \tau V_B N_\phi$, where
I = the photon-generated current in photoconductor
s = the distance between the electrodes, in meters;
q = the unit charge (=1 for I in electrons/sec);
μ = the charge mobility;
η = the quantum efficiency;
V_b = the applied (bias) voltage, and
N_ϕ = the number of photons/sec incident on the photoconductor.

Transfer efficiency
$TTE = (CTE)^{(r+c)}$

where CTE is pixel-to-pixel charge transfer efficiency; TTE stands for total transfer efficiency; and r, c are the numbers of rows and columns in the CCD, respectively.

Dark current

$\dot{d}_e = AT^{3/2}e^{-\frac{E_G}{2kT}}$ where $\dot{d}_e$ is the number of thermal electrons per second and A is a constant, use $A=4.3 \times 10^{10}$

Signal-to-noise ratio

$$SNR = \frac{N_*}{\sqrt{N_* + 2n_{pix}(b_e + d_e + \rho^2)}}$$

where N_* is the **total** number of electrons from the source and b_e, d_e, ρ^2 are the number of electrons **per pixel** from the sky, dark current, and read noise respectively and n_{pix} is the number of pixels in the digital aperture. (We've assumed here that the sky background, b_e, was also estimated from a region n_{pix} in size.)

Spectroscopy

spectral purity
$\delta\lambda = w_0\, p$ where
w_0 = the projected slit width on the detector
p = the linear dispersion, $d\lambda/dx$

resolving power
$R= \lambda/ \delta\lambda$

Free spectral range
$\Delta\lambda_{FSR} = \lambda_{max}/(m+1)$