PHY 300 Observational
Final Exam Revision - Optical
26 May 2015

This sheet covers the optical portion of the class, from Prof. Throop. Prof Booth will cover the radio portion separately.

I will supply a sheet with all equations and physical constants needed for the exam.

The **angular size** of an object is the angle subtended by it (e.g., the moon ha an angular size of roughly 0.5° as seen from Earth). The equation of angular size (theta = 1.22 lambda/d) give the result in radians; often want to convert to degrees or arcseconds.

The **angular resolution** of a telescope (or array) is a function of the wavelength and the diameter of the telescope (or array). The highest angular resolution (that is, the *smallest* theta) comes from using large-diameter telescopes with short wavelengths. Atmospheric **seeing** typically increases theta to 1-2", which is the smallest practical limit for many sites.

In Earth's atmosphere, the ***seeing*** *is the shaking of the* atmosphere. Typically this reduces the angular resolution from the theoretical limit to something less than that. Radio telescopes and radio telescope arrays often reach the theoretical limits (the **d**). Optical telescopes rarely reach the theoretical limits. But using **optical interferometry**, especially in space, these limits can sometimes be reached.

The simplest optical system is a **pinhole camera**. It works well, but has limited spatial resolution, and doesn't gather very much light. Lenses focus the light, so a larger aperture can be used.

In the 17th and 18th century, the first widely used telescopes were very long due to their **slow optics (i.e., large focal ratio**, such as f/20). A lot of this was because it was hard to manufacture high-performance fast optical systems at the time (e.g., f/2). Slower optics are closer to a pinhole camera, and thus less sensitive to any type of aberration (spherical aberration, chromatic aberration, etc.).

The first non-trivial optical system — like the **Galilean** telescope — were refractors, made with transmittive glass optics. The reflectors — like the **Newtonian** — changed the lenses for mirrors, which removes chromatic aberration (the 'prism effect'). Many modern telescopes use some variation on the **Cassegrain** telescope design, where two mirrors with two different focal lengths send the light through a donut-shaped hole in the primary, toward the focal plane. The telescope we used in class — a Schmidt-Cassegrain - is particularly compact. It uses a low-power glass lens on the front, coupled with two mirrors.

Spherical aberration was caused by early refractors which were curved to the shape of a sphere, not the (very similar) shape of a parabola. Modern designs use formulas of several linked optical components — or a parabolic mirror — to reduce spherical aberration. Parabolic mirrors have no spherical aberration, but they do have **coma**, for targets far from the center (that is, for rays which are coming in not parallel to the center of the mirror).

Refractors were easy to make, but dealing with **chromatic aberration** was (and remains) very difficult. Camera lens manufacturers deal with this by having a complex combination of lenses stacked so as to remove chromatic and other aberrations. High-performance telescope designers largely shifted to reflectors instead of refractors to get around the problem. **Reflectors** have their own problems (e.g., **diffraction spikes** from the support structure that holds the secondary), but by and large these can be dealt with.

Geometric optics can be used to describe the behavior of a lens or mirror. From a physics standpoint both are identical, in that they both focus light from parallel rays into a fixed point. The lens equation relates the focal length (a fixed quantity) to the positions of the object and image.

Broadly speaking, there are two types of telescope mounts. **Equatorial mounts (aka polar mounts)** are aligned with the Earth's N-S rotational axis. A motor drive allows them to rotate once per 24 hours, in which case you can image something easily for a long exposure without any adjustment other than running the motor. **Alt-Az mounts** are simpler mechanically, which makes them appealing for the largest telescopes, as well as many low-cost amateur ones. However, to follow a star through the sky, they must use a computer to track the sinusoidal motion of something as it rises and sets.

At the **focal plane** of a telescope, the image is formed. If we have a detector there (such as a film or CCD), the image can be recorded. Alternately, we can put an eyepiece there. The eyepiece diverges the light rays so they are parallel again, because your eye can see most easily when incoming rays are parallel (that is, for things up close, you must strain your eyes more!)

The **focal length** of a telescope (or mirror or lens) is a fixed quantity which is the distance to focus an image from infinity to the optical plane. For **compound optical systems** (like the Cassegrain), the focal length can be computed from the focal length of the individual components, and the distance between them.

Film (including glass **photographic plates**) was the reigning king of imaging fro most of the 18th century. It was displaced only in the last 10-20 years, when digital detectors such as the **CCD (charge-coupled device)** came into existence. The advantages of CCD over film is that they are linear, quantitative, and have a high quantum efficiency (QE). CCDs work over most of the visible wavelength range (0.3 - 0.9 micron) with a QE of 50%-90%. Similar digital detectors made of other materials work in the UV and IR. In all of these, using filters (such as UBVRI) to measure brightnesses in a range of wavelengths is common. Multiple images can be combined into a true-color or false-color image.

CCD are photon counters. They do this by storing the electrons that photons eject into an array of 'buckets' as a charge. After the integration is done, the charge is shifted out into an ADC (analog-digital converter) and read out, where it can be easily displayed on a computer as an image.

Although CCDs are quantitative, they are not perfect. Plenty of imperfections exist. Observers usually need to consider **dark-current, bias level, flat-fields, hot pixels, thermal noise, saturation, bleeding, gain, QE, bandpasses**, etc. when analyzing CCD data.

CCDs make it easy to measure the **Poisson noise** of an observation, which can be used to calculate the SNR (signal-to-noise ratio). Noise can come from many factors. If photons statistics is the dominant term, then the noise level (that is, the 1 sigma typical variation) for N photons is sqrt(N).

Impact craters are caused by the explosive deceleration of projectiles (typically rock or ice, from asteroids or comets) into the surface of a planet or other body. Most of the energy goes into mechanical excavation of the crater. Typical impactor speeds are 5-50 km/sec, based on the escape velocity of the body, and the orbit of the impactor. Although no one has ever been killed in an impact, there is a measurable threat to humanity from them. '**Shooting stars'** refer the meteor tail of small impactors, mm-cm sized, that burn up in the Earth's atmosphere and never hit the ground.

Magnitude system. Historically, bright stars were classified as 'first magnitude', slightly fainter as 'second,' and so forth. While quantitatively this is reversed from normal measurement methods (where brighter stars would have a larger number), such is history! Each magnitude corresponds to a decrease in flux (or equivalently, brightness or intensity) by a factor of ~2.5, such that 5 magnitudes is a factor of 100. Astronomers oten measure magnitude in several different bands (e..g, UV, near-IR, visible, green, blue), using color filters.

To zeroth order, **stars can be considered to be black bodies**, radiating with a black-body spectrum at their given temperature. The hottest stars are bright in the UV (and thus look blue) and can have temperatures of > 10,000 K. These stars are massive, but short-lived. The coolest stars are bright in the near-IR. Although low-mass to star with (<1 m_sol), they have a long lifetime because nuclear processes occur much slower in their core than in that of the hottest stars.

While we see the shift in perspective of the planets due to the Earth's changing position through space (2 AU in 6 months), it's very hard to see such a shift in the positions of the stars, which are much further away. One exception to this is the relatively small number of stars which are nearby enough to measure their **parallax shift**. For stars with a 1" shift, their position is defined as being 1 parsec (1 pc) = 3.26 ly.

Redshift or blueshift (due to objects traveling a measurable fraction of the speed of light) is important for distant galaxies, and (to a much much smaller extent) the wobble of stars at the center of exoplanet systems. In our solar system and local region of the galaxy, while redshift may be occasionally measurable, it is small and not important to most calculations.

Flux is the amount of energy per area. Flux from a point source (or far away from a source) can be calculating using an inverse square law. For flux reflecting from a surface before reaching the observer, the inverse square law can be applied several times sequentially (e.g., flux from the Sun, reaching Pluto, then reflecting back to Earth).

Thermal energy balance of a body (such as a planet or moon) can be used to calculate its **equilibrium temperature**. In equilibrium, the energy in (from optical) must by definition be equal to the energy out (radiated from thermal).

Albedo is the fractional reflectivity of an object. It could be measured at each wavelength, but is often averaged over bands or over the entire visible wavelength range. Albedo of the moon is around 0.05; that of white paper is around 0.9.

The universe has many distance scales. Be familiar with the **size scales and timescales** of the planets, the solar system, the Milky Way, galaxies, and the universe. (e.g., how many ly is the galaxy across? How old is the universe? etc.)

Specific objects we observed and talked about

- Jupiter and moons
- Venus and phases
- Saturn, Titan, rings
- Orion nebula and stellar nursery
- Jewel Box
- Milky Way
- Southern Cross
- South celestial pole.

Earth's seasons are caused by its tilt, not its distance to the Sun. You should be able to explain them.

The **Moon's phases** are caused by the Moon's monthly motion around the Earth. The Moon is in synchronous rotation with the Earth — that is, it has exactly one revolution per orbit, so the same side is always facing Earth. The moon rises at different times based on its phase.

Kepler's laws of motion govern the behavior of one body in orbit around a much larger one. In most of what we have done, we are interested in the **orbital period and orbital velocity,** which can be easily calculated from first principles. The laws of motion are the same for moons orbiting Jupiter, for the Earth orbiting the Sun, and for exoplanets orbiting distant stars.

In the last 20 years **exoplanets** have been discovered around several thousand nearby stars (within 1000 ly or so). The first discoveries were from the subtle red/blueshift of the **central stars wobbling** as they were tugged by the planets. Since then, the vast majority have been discovered by **transit photometry** from the Kepler mission.

Right ascension and declination are the two axes (similar to X and Y, or longitude and latitude) that we use to find our way around in the sky. These were covered in an early PS, but will not be on the exam.