The final exam for ASTR-1200 takes place in room Duane G1B20 on **Wednesday, May 8, 2019** from 1:30 to 4:00 pm. The exam covers everything discussed in the course, including the material for Midterms 1, 2, and 3, as well as new material from the parts of Chapters 22 and 23 in *The Cosmic Perspective* that were assigned as readings. The exam draws on the readings, lecture material, clicker questions, and concepts in the homework. Please come to office hours, the Astronomy Help Room, and/or the extra pre-exam review session if you need assistance with this material.

The exam will consist mainly of multiple-choice questions, and a few short-answer questions that require you to write a couple of sentences for each. The midterm exams are closed-book and closed-notes. **You will be allowed to bring in one sheet of handwritten notes** ($8.5'' \times 11''$, both sides). You can bring a calculator, but you should not need one. Of course, no phones or laptops (or any device that connects to the outside world) are allowed.

Some of the questions will involve memorization, but these ought to be concepts that we have highlighted and/or repeated as being major topics. Other questions will involve you taking what you know and applying it in a slightly different way.

Below is a list of sources for study aids, followed by a "birds-eye-view" list of topics that we covered. If you review and understand every item in those lists (along with where they appear in the lecture-note PDFs), you should be in good shape for the exam.

SOURCES FOR STUDY ASSISTANCE

- **Textbook**
  - "Learning Goals" (start of every chapter)
  - "Big Picture" and "Summary of Key Concepts" (end of every chapter)
  - "Common Misconceptions" and "Think About It" boxes
- **Canvas**
  - All lectures notes are posted in PDF format
  - Review the clicker questions from lectures
  - Solutions to the homeworks will be posted
  - All three midterm exams (with answers) have been posted, too
  - Feel free to use the "Discussions" tab to chat online, post questions, find study partners, etc.
- **Study Groups**
  - You are encouraged to study with classmates, but be sure to take turns asking and answering questions. When done right, this can be one of the best ways to learn.
- **Office Hours & Help Sessions**
  - **Prof. office hours:** Tues. & Fri., 10:00-11:00 (Duane D111)
  - **TA office hours:** Mondays, 10:00-12:00 (Duane D232)
  - **TA pre-exam review session:** TBD TBD TBD
  - **Astronomy Help Room:** Tues., Wed., & Thurs., 2:00-6:00 (Duane D142)

TOPICS/CONCEPTS FOR MIDTERM EXAM 1

Chapter 1: Overview (sections 1.1, 1.2, 1.4)

- Scientific notation, powers of ten, and how they are manipulated.
- Ratios and scaling relations. Understand how to work with expressions that use the "proportional-to" symbol ($\propto$) below.
- Our place in the Universe. Ranking various major classes of objects (planets, stars, galaxies, clusters) in size and distance.
- Common distance units: AU and light-year (know their meanings, *not* their exact values). For the light-year, know where it comes from: *speed = distance / time,* so *distance = speed* $\times$ *time.*
- Understand that when we look deeper into space, we're looking further back in time. Since the Big Bang was 14 billion years ago, that means the "Observable Universe" extends only 14 billion light-years from us in any direction.

Chapter 2: Looking up at the Night Sky (section 2.1)

- What is the celestial sphere? Can we see all of it from one vantage point on the Earth? Why do objects in the sky rise in the east and set in the west?
- Understand how & why the Earth's tilt causes the seasons.
- We use angles (degrees, arc-minutes, arc-seconds) to measure the apparent sizes & distances of objects on the celestial sphere. However, angles alone cannot tell us the *distances* to these objects.

Chapter 3: History of Astronomy (sections 3.1 [first page only], 3.2)

- Ancient Greek astronomy: Understand their geocentric & heliocentric models of the universe. The observed *retrograde* motion of some planets required them to add *epicycles.*
- Astronomy in the 1500s-1600s: Understand the general roles played by Copernicus, Tycho, Kepler, and Bruno.
- Know how Galileo's use of the telescope provided much more evidence for the heliocentric model. However, he couldn't prove it conclusively because he could not measure the *parallax* motion of stars.
- All of this resulted in the development of the modern Scientific Method.

Chapter 4: Motion, Gravity, and Energy (sections 4.1, 4.3 [pages 119-123 only])

- Motion is measured with distance (d), time (t), velocity ($v = d/t$), and acceleration ($a = v/t$). Any change in velocity (including just changing direction of motion) counts as acceleration.
- Know how Newton's three laws of motion describe the concept of *force:* (1) If no force, velocity is constant. (2) Forces cause acceleration ($F = ma$). (3) If X exerts a force on Y, then Y exerts an equal/opposite force on X.
- Any two massive objects (masses m_1 & m_2) separated by a distance (d) exert a gravitational force on one another that scales as $F \propto m_1 m_2 / d^2$.
- On Earth, the acceleration due to gravity is about 10 m/s^2, and it's independent of the mass of the falling object. If you drop something, its speed increases at a rate of 10 m/s every second.
- An *orbit* is just a falling body with enough sideways speed to keep falling "around" a spherical object, perpetually.
- Understand the main types of energy (kinetic, radiative, potential). The total energy of a system is always conserved, but energy can change from one type to another.

Chapter 5: Light and Atoms (sections 5.1, 5.2, 5.3, 5.4)

- How does light interact with matter? Understand emission, absorption, transmission, & scattering.
- Light can be described as both waves and as particles ("photons").
- For light waves, understand how wavelength (λ), frequency (f), and the speed of light (c) are related to one another: $c = \lambda f$, and so on.
- The energy of a photon: $E \propto f \propto 1/\lambda$.
- Know the main layout of the electromagnetic spectrum: gamma-rays, X-rays, ultraviolet, visible, infrared, microwave, radio.
- Recall the roles of protons, neutrons, and electrons in atoms.
- Electrons "orbit" the nucleus with a range of possible *energy levels.* If electrons jump UP, that's an energy gain that must correspond to absorbing (destroying) a photon of that energy. If electrons jump DOWN, that's an energy loss that must correspond to emitting (creating) a photon of that energy.
- Hot, solid objects glow with a continuous thermal ("blackbody") spectrum, with $\lambda_{\rm peak} \propto 1/T$, and total intensity $I \propto T^4$.
- Understand how emission and absorption line spectra are created.
- Understand the basic reasons for the *Doppler shift* of light: motions toward the observer are blue-shifted, and motions away from the observer are red-shifted.

Chapter 6: Telescopes (sections 6.1, 6.2)

- Know the 3 main reasons that we use telescopes. Compared to the human eye, (1) they collect more light, (2) they have better angular resolution, and (3) they can be made sensitive to non-visible wavelengths.
- The light-collecting power of a telescope is proportional the *Area* of its main mirror or lens. Remember that $A = \pi r^2$, and that a circle's diameter is twice its radius.
- Some wavelengths of light (all gamma-rays, all X-rays, some UV, some IR, and some radio) are absorbed totally by the Earth's atmosphere, so telescopes must be put in space in order to detect that light from distant objects.

TOPICS/CONCEPTS FOR MIDTERM EXAM 2

Chapter 14: The Sun (sections 14.1, 14.2, 14.3)

- General properties of the Sun, and the wavelengths of light we see, as covered in class.
- Why does the Sun generate light? Review early (but wrong) ideas, as well as the correct idea.
- Nuclear fusion of H into He. How is $E = mc^2$ relevant? Why does the temperature have to be so high? Don't worry about detailed steps in the chain; just know the general inputs and outputs.
- How does the energy generated in the core get out? Know the layers up to the surface: core, radiative zone, convective zone, photosphere.
- Hydrostatic equilibrium: a balance betwen gravity (inward) and the pressure-gradient force (outward).
- The solar thermostat: an example of "negative feedback."
- How do we know what's going on inside the Sun? Neutrinos and helioseismology.
- Layers above the solar surface: photosphere, chromosphere, corona, and solar wind. Some of them can be observed only with total eclipses or from space (at UV/X-ray wavelengths).
- Know basic ideas about the 11-year sunspot activity cycle, and how magnetic fields are involved.
- Know some of the ways that variability in solar activity can cause dangerous "space weather" effects to human life, society, & technology.

Chapter 15: Surveying the Stars (sections 15.1, 15.2, 15.3)

- Understand how parallax (p) is used to measure distances (d) to stars, and know that $p \propto 1/d$.
- A star's luminosity (L) is a fixed constant, but its apparent brightness (B) is smaller as you get further away. They're linked by the inverse-square law, $B = L/(4\pi d^2)$.
- Stellar surface temperatures can be measured from colors and spectral lines. The spectral types go from hottest to coldest as OBAFGKM.
- Stellar masses can be measured (for binary stars or stars with planets) with Newton's laws. If we know any 2 out of 3 for an orbit's {size, speed, period}, we can compute the mass of the orbiting objects.
- The Hertzsprung-Russell (H-R) Diagram is a useful way to organize stars by surface temperature T and luminosity L.
  - Stars are thermal blackbodies, so $L \propto R^2 T^4$. This lets us compute radius R for any point in the H-R Diagram.
  - The main sequence is where most "adult" stars live. Giants/supergiants live in the upper-right (largest R), and white dwarfs live in the lower-left (smallest R).
- Stellar lifetimes: More massive stars have more hydrogen fuel, but they burn it up *MUCH* faster, so they have the shortest lifetimes. For O→G→M types, the lifetimes are Myr→Gyr→Tyr.
- Stellar ages: star clusters are useful because we can see their "main-sequence turnoff" and measure their ages.

Chapter 16: Star Birth (sections 16.1, 16.2, 16.3)

- Molecular clouds and their role in star formation.
- As a cloud collapses, its core heats up, so it goes from its initial stage (big & cold) with gravity "winning," to its final stage (dense & hot) with a balance between gravity and pressure.
- What are likely ways for the collapse to be triggered?
- Know the role of angular momentum conservation in creating a flat "accretion disk" of gas around the newly-born star. This disk eventually condenses into rings of dust, rocky bits, and (possibly) planets.
- Mass range for newly-born stars:
  - Low end ($M < 0.08\,M_{\rm sun}$): brown dwarfs; cores are too cold to fuse H $\rightarrow$ He.
  - High end ($M > 150\,M_{\rm sun}$): so luminous that "radiation pressure" is stronger than gravity.
  - Distribution of masses: many more at the low end. 200 M-stars for every O-star.

Chapter 17: Stellar Evolution (sections 17.1, 17.2, 17.3, 17.4)

- Evolution of a star after it runs out of hydrogen in the core:
  - Low-mass (0.08–3 $M_{\rm sun}$): H-main-sequence $\rightarrow$ red giant $\rightarrow$ helium flash $\rightarrow$ horizontal branch (He-main-sequence) $\rightarrow$ double-shell red giant $\rightarrow$ planetary nebula & white dwarf.
  - High-mass (3–150 $M_{\rm sun}$): H-main-sequence $\rightarrow$ red supergiant $\rightarrow$ core-burning for He, C, O, and higher-mass elements up to iron $\rightarrow$ core-collapse supernova $\rightarrow$ neutron star or black hole.
- Know which stages are "in balance" and which are "out of balance" (regarding pressure vs. gravity).
- Why are low-mass and high-mass stars different? Each type of fusion "switches on" only above a critical core temperature. Low-mass stars sometimes don't reach it; high-mass stars do.
- Know why iron is important as the end-stage for energy-generation by nuclear fusion in stars.
- Know that *you* are made of the elements fused in the cores of an older generation of massive stars.
- Evolution in close binaries: sometimes they look wrong! Low-mass red giant with a high-mass main-sequence star? The low-mass star started out with more mass, evolved more quickly, and donated mass to its companion!

Chapter 18: White Dwarfs & Neutron Stars (sections 18.1, 18.2 only)

- What are the formation scenarios that lead to white dwarfs, neutron stars, or black holes?
- White dwarf (WD): gravity vs. electron-degeneracy pressure
  - Single WD's just cool down into "black diamonds."
  - The Chandrasekhar limit: WD mass must be $< 1.4\,M_{\rm sun}$
  - In binaries, an accreting WD may become a *nova* (explosion of thin layer of accreted hydrogen) or a *supernova* (mass exceeds 1.4 $M_{\rm sun}$ and the whole thing explodes)
- Neutron star (NS): gravity vs. neutron-degeneracy pressure
  - Single NS's cannot exceed approx. 3 $M_{\rm sun}$
  - Core collapse speeds up NS rotation and intensifies its magnetic field. Both of these effects mean that some NS's appear to us as *pulsars* (emitting narrow beams of radio waves).
  - Two NS's in a binary may merge together, creating a *kilonova* and associated gravitational waves.

TOPICS/CONCEPTS FOR MIDTERM EXAM 3

Chapter S2: Special Relativity

- The Michelson-Morley experiment. It showed that light always travels at the same speed, no matter the motion of the source or observer ("$c = c = c$").
- Implications of special relativity: time dilation, length contraction, mass increase (perceived for something moving with respect to the observer). Nothing can go faster than c.

Chapter S3: General Relativity

- Einstein's Equivalence Principle: the effects of gravity are indistinguishable from the effects of acceleration.
- We live in 4-dimensional spacetime, and gravity curves it ("rubber sheet model"). Objects want to travel along the straightest possible path.
- The paths of both matter and light beams can be curved by gravity. This produces effects like gravitational lensing, gravitational time dilation, and the precession of Mercury's orbit.

Chapter 18: Black Holes & Gravitational Waves (sections 18.3, 18.4 only)

- What is a black hole? Know the role of escape velocity and the definition of the event horizon. How are objects "spaghettified" when they fall in?
- Do black holes really exist? Review the observational evidence (massive-star binary systems).
- Gravitational waves: what are they; what can generate them (NS-NS or BH-BH binary mergers); how has LIGO detected them? *(Too recent to be in the textbook... see lecture notes!)*

Chapter 19: the Milky Way Galaxy (sections 19.1, 19.2, 19.3, 19.4)

- How did we determine the size & scale of the Milky Way? Where are we with respect to the center?
- General structure of the Milky Way: bulge, disk (with spiral arms), and halo (with globular clusters). How much gas/dust is in each region? What types of stars are in each region?
- How can we use our solar system's orbital motion to calculate the mass of our galaxy?
- Overview of star–gas–star cycle and the multiple "components" of the interstellar medium.
- Spiral arms are density-wave "traffic jams," not rotating spokes. Know about how new stars are formed as gas passes through the spiral arms, and why the star-forming regions are blue.
- Sagittarius A*: How do we know there is a supermassive black hole at the galactic center? How did we determine its mass?

Chapter 20: Other Galaxies & the Expanding Universe (sections 20.1, 20.2, 20.3)

- Galaxy classification: spiral, elliptical, lenticular, irregular. Know basic properties of each type.
- Who are our neighbors in the "Local Group?"
- When plotting galaxies on an H-R diagram (luminosity vs. color), know what's going on with the blue cloud vs. the red sequence. Why are galaxies in the latter group called "red & dead?"
- The Cosmic Distance Ladder: how we measure distances from near to far...
    - Radar ranging and parallax
    - Standard candles: main-sequence fitting & the tip of the red-giant-branch
    - Cepheid variables: Leavitt's period–luminosity relation
    - White dwarf supernovae: the brightest standard candles of all
- Main contributions of Edwin Hubble: (1) classified galaxies with "tuning fork" diagram, (2) used Cepheids to measure distances to nearby galaxies, (3) discovered *Hubble's Law:* more distant galaxies are moving away from us faster.
- Know basics about Hubble's constant H_0 and how to estimate the age of the universe from it.
- Some effects of the expansion of the universe:
    - Cosmological redshift stretches out all distances over time
    - The total distance to the "cosmic horizon" can be huge (bigger than just light-travel-time over the age of the universe)
    - The Cosmological Principle says we should see the same expansion no matter where we are

Chapter 21: Galaxy Evolution & Quasars (sections 21.1, 21.2, 21.3)

- There is evidence that many galaxies evolved by undergoing collisions & mergers. In the early universe, galaxies were smaller & more irregular than they are now.
- The Milky Way will someday collide with the Andromeda Galaxy. First there will be a brief "starburst" phase, but then the gas will get used up. Eventually there will just be one big, merged elliptical galaxy with no more gas or star formation.
- Most galaxies have supermassive black holes (SMBHs) at their centers. More massive galaxies have more massive SMBHs.
- If a SMBH is swallowing lots of gas from a surrounding accretion disk, some of the gas will be converted to energy ($E = mc^2$) and make an Active Galactic Nucleus (AGN):
    - Most of the time, we see an AGN as a bright source called a *quasar.*
    - If we're looking directly down its narrow radio jet, we see an even brighter *blazar.*

TOPICS/CONCEPTS FOR FINAL EXAM

Chapter 22: The Big Bang

- Basic idea: the universe was once much smaller, hotter, and denser than it is now.
- Evidence: (a) Hubble's expansion, (b) Olber's paradox, (c) the Cosmic Microwave Background (CMB), (d) the abundance of helium produced in the early universe.
- The different eras (what happened in each one; what caused the transitions):
  1. **Planck Era:** Requires theory of Quantum Gravity, which we don't have.
  2. **GUT Era:** Strong, weak, & electromagnetic forces are unified.
  3. **Electroweak Era:** Weak & electromagnetic forces are unified. At end, all 4 forces are separate.
  4. **Particle Era:** Free quarks, electrons, & their anti-particles dominate. At end, nearly all antimatter has been annihilated, and we're made up of the small fraction of normal matter left over.
  5. **Era of Fusion:** Quarks become confined into protons & neutrons, and the neutrons decay (over 20 minutes), then fuse with protons into helium.
  6. **Era of Nuclei:** Too cool for fusion, but too hot for neutral atoms. Plasma is opaque to light. At end, plasma becomes transparent: CMB is formed.
  7. **Era of Atoms:** Universe is transparent & atoms are neutral, but no new light is being emitted ("Dark Ages").
  8. **Era of Galaxies:** Stars & galaxies form. Their photons re-ionize the hot gas between galaxies. This stage is the majority of the time between the Big Bang and now.
- Inflation: Was there a rapid expansion of the universe during stages 2–3? If so, all sizes ballooned up by a factor of 10^{30} to 10^{50}. This may explain: (a) the horizon problem (i.e., why the universe is so uniform), (b) the density enhancement problem (i.e., what determined the tiny CMB fluctuations that led to galaxy clusters), (c) the flatness problem (i.e., why is 3D geometry so simple & "flat").

Chapter 23: Dark Matter & Dark Energy

- What do we mean when we talk about dark matter and dark energy?
- Evidence for dark matter: (a) rotation curves of individual galaxies, (b) orbits of galaxies in clusters, (c) pressure of hot gas in galaxy clusters must be balanced by gravity, (d) clusters create a lot of gravitational lensing.
- What is dark matter? MACHO's vs. WIMPS, or maybe the theory of general relativity needs tweaking?
- Evidence for dark energy: For the most distant galaxies, Hubble's law breaks down and shows the expansion of the universe is *accelerating.*
- What is dark energy? An unknown repulsive force ("anti-gravity," but for spacetime, not matter)?
- Fate of the universe: Will it keep expanding, or eventually recollapse?