General Qualifying Exam Question Bank for 2018

I. Cosmology

1. What is recombination? At what temperature did it occur? Explain why this does not match the ionization potential of hydrogen.
   - How is the CMB related to recombination?
   - Around how long ago/what redshift did this happen?

2. The universe is said to be "flat", or, close to flat. What are the properties of a flat universe and what evidence do we have for it?

3. Outline the development of the Cold Dark Matter spectrum of density fluctuations from the early universe to the current epoch.
   - How do we observe the power spectrum?
   - What is its relation to BAOs and the C_l power spectrum?

4. State and explain three key pieces of evidence for a Big Bang origin for the observable Universe.

5. Define and describe the "tired light hypothesis" and the "steady state universe" as alternatives to the Big Bang. How have they been disproved observationally?

6. Why are only very light elements (H, D, He, and traces of Li) synthesized in the first three minutes of the Big Bang?

7. Explain how and why Type Ia Supernovae are used in the measurements of cosmological parameters.
   - What are Type Ia SNe (i.e. what is physically happening)?
   - Can SNe Ia constrain *all* cosmological parameters?
   - What are some source of error?

8. Describe two methods, other than Type Ia supernovae, by which the cosmological parameters can be determined by astronomical observations.

9. Why is the cosmic microwave background expected to be weakly polarized, and what is practically required to observe this signal?
   - What are some foregrounds or challenges to observing this signal?
   - Why does dust polarize the CMB?
   - Why is dust not randomly oriented?
   - How did we first determine that dust wasn't randomly oriented?

10. Our view of the cosmic microwave background is affected by what is along the line of sight. Give two examples of CMB foregrounds that also provide information about the cosmic parameters.

11. Describe cosmological inflation. List at least three important observations it is intended to explain.

12. Define and describe a 'fine tuning problem'. How do anthropic arguments attempt to resolve it?
    - What are other fine-tuning problems?
    - How do you *feel* about the anthropic principle?

13. Define the two-point correlation function. How is it related to the power spectrum? How is the C_l spectrum of the CMB related to low redshift galaxy clustering?

14. Consider a cosmological model including a positive cosmological constant. Show that, in such a model, the expansion factor eventually expands at an exponential rate. Sketch the time dependence of the expansion factor in the currently favoured cosmological model.

15. Define and describe the epoch of reionization. What are the observational constraints on it?

- Besides the first stars and galaxies, what else could have ionized the universe?
- How does the recent Nature paper by Bowman et al. relate to this?

16. The 21 cm line of hydrogen is expected to show up in absorption against the cosmic microwave background at some redshifts, and in emission at other redshifts. What physical processes lead to this behaviour?

17. What is the difference between scalar and tensor modes of perturbation in the early universe, and how can you detect their presence?

18. What are the similarities and differences between the cosmic neutrino background and the cosmic microwave background?

- What is a neutrino?
- How do we determine their mass?
- Besides the sun and CNB, what other sources of neutrinos are there in the universe?
- What is the neutrino contribution to the density of the universe?
- Why do the neutrinos decouple at 1 second/before photons?

19. What is the difference between an isocurvature mode and an adiabatic mode, in terms of the initial density perturbations in the early universe? How do we know that the initial conditions are mostly adiabatic?

20. Give three examples of possible dark matter candidates (current or historical). What is their status observationally?

- How do neutrinos fit into this picture?
- Hot DM vs Cold DM
- What is MOND and how does it fit in with DM?
- What happens if we don't find WIMPS? Or, how is this going?

II. Extragalactic

1. Sketch out the Hubble sequence. What physical trends are captured by the classification system?
    - What physical trends does the Hubble sequence show that were *not* explicitly encoded in it? That is, are there any other physical properties that the Hubble sequence ended up telling us by accident?

2. What is the total mass (in both dark matter and in stars) of the Milky Way galaxy? How does this compare to M31 and to the LMC? How is this mass determined?

3. Describe as many steps of the distance ladder and the involved techniques as you can. What are the rough distances to the Magellanic Clouds, Andromeda, and the Virgo Cluster?

4. What evidence is there that most galaxies contain nuclear black holes? How do those black holes interact with their host galaxies?

5. Define and describe globular clusters. Where are they located? What are their typical ages, and how is this determined?

6. Describe three different methods used in the determination of the mass of a galaxy cluster.

7. What is the density-morphology relation for galaxies? How is that related to what we know about the relationship between galaxy density and star formation rates in galaxies?

- What processes in a cluster convert galaxies?
- Where is galaxy harassment most effective (due to relative speeds)?

8. Draw the spectral energy distribution (SED) of a galaxy formed by a single burst of star formation at the ages of 10 Myrs, 2 Gyrs, and 10 Gyr. Please highlight the change over time in the 4000 Angstrom break.
   - Why do we only consider a single burst of SF (answer: population synthesis)?
   - If you looked at an actual SED, what else would you see besides the mostly smooth continuum and spectral breaks?
   - What's a typical emission line you would see in the optical part of the spectrum?
   - Why is the y-axis in λF_λ, what does that mean?

9. How are galaxy redshifts estimated by photometric techniques?
   - What problems are there with the photometric method?
   - How do you account for different galaxy types and what do you need to know about the stellar population (answer: IMF)?

10. Draw a spectrum of a high-redshift quasar. What do quasar emission lines typically look like? Explain what we see in the spectrum at rest wavelengths bluer than 1216 Angstroms.

11. Sketch the SED from the radio to gamma of extragalactic radiation on large angular scales. Describe the source and emission mechanism for each feature.

12. What are AGNs? Describe different observational classes of them and how they may relate to each other.
   - What are the physical scales of the SMBH, accretion disk, and jet?
   - How massive are SMBHs?
   - Why is there a connection between bulge properties and SMBH mass?
   - How do you determine over what range SMBH potential is important?

13. What are galaxy clusters? What are their basic properties (eg, mass, size). List and explain three ways they can be detected.
   - Where does X-ray gas come from? How do we see it/what is its emission mechanism?
   - How is the X-ray gas initially heated/why is it hot?

14. What is star formation quenching? What is the evidence for it, and why is it thought to happen?
   - What is the star formation history of the universe, how does it evolve with time (wanted to hear Lilly-Madau plot)?
   - At what redshift was the rate of star formation highest?
   - How does this relate to the population of stars we see today (how old is the sun, which stars are most common)?

15. Provide three examples of ways in which feedback processes are important on galactic and intergalactic scales.
   - What is the star formation rate in a galaxy (derive)?
   - How fast would all the gas be eaten up if there was no feedback?
   - How could you observationally constrain metal enrichment of the IGM?
   - How do these processes affect a single galaxy vs cluster?
   - If feedback sets an effective maximum mass for a galaxy, can you draw a cooling curve (density versus temperature)?

III. Galactic

1. What is a stellar Initial Mass Function (IMF)? Sketch it. Give a couple of examples of simple parametric forms used to describe the IMF, such as the Chabrier, Kroupa, or Salpeter functions.

- How did Salpeter determine the IMF?
- How do you normalize the IMF?
- Is the upper or lower limit (on mass) more important for the normalization?

2. Describe the orbits of stars in a galactic disk and in galactic spheroid.

3. Every now and then a supernova explosion occurs within 3 pc of the Earth. Estimate how long one typically has to wait for this to happen. Why are newborn stars likely to experience this even when they are much younger than the waiting time you have just estimated?

4. Galactic stars are described as a collision-less system. Why? (Don't forget the influence of gravity.)

5. Given that only a tiny fraction of the mass of the interstellar medium consists of dust, why is dust important to the chemistry of the medium and to the formation of stars?
   - Why is molecular hydrogen difficult to detect?
   - What other ways can molecular cloud cores cool?

6. The ISM mainly consists of hydrogen and helium, which are very poor coolants. How, then, do molecular cloud cores ever manage to lose enough heat to collapse and form stars? Why are H and He such poor coolants?

7. The stars in the solar neighbourhood, roughly the 300 pc around us, have a range of ages, metallicities and orbital properties. How are those properties related?

8. What are the main sources of heat in the interstellar medium?
   - Are there any non-ionization sources of heat in the ISM (shock waves)?
   - How do shock waves heat gas? Are shock waves adiabatic?
   - Where do the x-rays for x-ray photoionization come from?
   - What phases of the interstellar medium and temperatures apply to each example?

9. Draw an interstellar extinction curve (ie, opacity), from the X-ray to the infrared. What are the physical processes responsible?
   - What happens at even shorter wavelengths, like gamma rays?

10. What is dynamical friction? Explain how this operates in the merger of a small galaxy into a large one.

11. Sketch the SED, from the radio to Gamma, of a spiral galaxy like the Milky Way. Describe the source and radiative mechanism of each feature.

12. How many stars does one expect to find within 100 pc of the Sun? If all stars are distributed evenly across the galaxy, how many of these will be B spectral type or earlier? How many are younger than 100 Myrs?
   - Justify your assumptions. Do these match observation? If not, why?
   - Where are most B-type and earlier type stars actually found?
   - How do we know how many stars there are in the MW?
   - How do we measure the IMF? Are high or low mass stars more important to constrain to accurately estimate N_{star}?
   - How many B stars visible from your backyard? Any SF regions visible from your backyard?

13. Describe what happens as a cloud starts to collapse and form a star. What is the difference between the collapse and contraction stages? What happens to the internal temperature in both? When does the contraction phase end, and why does the end point depend on the mass of the object?

14. Sketch the rotation curve for a typical spiral galaxy. Show that a flat rotation curve implies the existence of a dark matter halo with a density profile that drops off as 1/r^2.

- What assumptions do you make in deriving the $1/r^2$ profile?

15. What thermal phases are postulated to exist in the interstellar medium? Describe the dominant mechanism of cooling for each phase.

16. Characterize the stellar populations in the following regions: i) the Galactic bulge ii) the Galactic disk, outside of star clusters iii) open star clusters iv) globular clusters v) the Galactic halo vi) a typical elliptical galaxy.

17. How can one determine the temperature of a HII region?

18. What is the G-dwarf problem in the solar neighborhood?

19. Describe the general characteristics of spiral structure in galaxies.

IV. Stars and stellar astronomy

1. Sketch out a Hertsprung-Russell diagram. Indicate where on the main sequence different spectral classes lie. Draw and describe the post main-sequence tracks of both low- and high mass stars.

2. Sketch a plot of radius versus mass for various "cold" objects made of normal matter, including planets, brown dwarfs and white dwarfs. Explain the mass-size relationship for rocky and gaseous objects. Why is there an upper mass limit?
   - How do you calculate the Chandrasekhar mass limit?
   - Why is Saturn smaller than Jupiter, or why do we see a range of radii in extrasolar planets?

3. Describe the physical conditions that lead to the formation of absorption lines in stars' spectra. What leads to emission lines?
   - Why isn't an absorption line a delta function?
   - How does this relate to population levels and excitation temperatures?
   - Are there emission lines in the Sun? Why is there emission from the Calcium doublet?

4. Describe these important sources of stellar opacity: electron scattering, free-free, bound-free, and the H- ion.

5. Describe the processes that can cause pulsations in a star's luminosity, and provide at least one example of a class of stellar pulsation.
   - What about RR Lyrae stars?
   - What is the period-luminosity relation?
   - What is the form of the period-luminosity relation?
   - How would you derive the time scale of pressure waves in a star?
   - How would you order-of-magnitude estimate the period for a pulsation?

6. Briefly describe the sources of thermal energy for stars and planets.

7. Describe the process by which supernovae produce light. Why are Type Ia supernovae generally brighter than Type II events?

8. Describe the condition for a star's envelope to become convective. Why are low mass stars convective in their outer envelopes while high mass stars are convective in their inner cores?

9. What is Eddington's luminosity limit? Explain why this limit is important for the properties and lifetimes of massive stars.

10. Explain why we know what the Sun's central temperature ought to be, and how we know what it actually is.

11. Which have higher central pressure, high-mass or low-mass main-sequence stars? Roughly, what is their mass-radius relation? Derive this.

- How would we actually know the central pressure?
- What properties can we measure to test models of stellar structure?

12. Sketch the SED of an O, A, G, M, and T star. Give defining spectral characteristics, such as the Balmer lines and Balmer jump and Calcium doublets, and describe physically.

- Are there emission lines?
- What molecular lines are in the Sun?
- What important lines are there at much longer wavelengths than visible?
- What if the A star had a protoplanetary disk?
- What is the significance of a νF_ν (or lambda F_{lambda}) spectrum?
- How can the relative height of the stellar vs disk bumps change? (Total energy out of system will be constant; dust bump can't be higher than star bump with no extinction)

13. What can be learned about young stars (T Tauri and pre-main-sequence stars) from an analysis of their spectral features?

14. Sketch the spectral energy distribution (SED) of a T Tauri star surrounded by a protoplanetary disk. How would the SED change: (a) if the disk develops a large inner hole, (b) if the dust grains in the disk grow in size by agglomeration (with the same total mass)?

15. What are the primary origins of the heat lost to space by infrared luminosity of Jupiter, Earth, and Io?

16. Explain the observational problem of radius inflation for hot Jupiters and describe two possible solutions.

17. Explain the effects of an atmosphere on a planet's surface temperature and the position of the "habitable zone". What special considerations must one make for habitability around M-type stars?

18. Explain the process of nuclear fusion and give two examples of important fusion processes that affect the lives of stars.

19. What is Fermi's Paradox? Explain its logic and assess the current state of the Paradox in light of modern knowledge.

20. The so-called r- and s- processes are mechanisms that produce elements heavier than iron. Describe these mechanisms and evidence for them from abundance patterns. Where is the process thought to act?

V. Physics

1. Draw the geometry of gravitational microlensing of one star by another, and estimate the angular displacement of the background star's image.

- Can you derive phi from a Newtonian approach?
- Why/how does gravitational lensing magnify a star?

2. A two-element interferometer consists of two telescopes whose light is combined and interfered. Sketch the response of such an interferometer to a nearby red giant star, as a function of the (projected) separation between the two telescopes. The red giant subtends one-fiftieth of an arc second on the sky, and the telescope operates at a wavelength of 2 microns.

- What do the minima in the response function tell you?

3. What's the minimum mass of a black hole you could survive a fall through the event horizon without being ripped to shreds? Why would you be ripped to shreds for smaller black holes? How does this relate to the BH mass range for which we expect tidal disruption flares caused by shredding main-sequence stars?

- How would you estimate the maximum tidal acceleration a star can withstand?
- Why is it enough to know if the surface of the star can be disrupted?

4. How is synchrotron radiation generated, and how was it used to demonstrate the energy required to power radio galaxies?

5. What are "forbidden lines" of atomic spectra? In what conditions are they observationally important? In what conditions do they control the temperature of interstellar material?

- What are some common examples of forbidden lines?
- When do you get forbidden line absorption?
- Can we observe any forbidden lines on Earth?
- What is the lifetime of 21 cm line?
- How would you estimate lifetime from maximum density where line isn't washed out?
- Collisions happen much more frequently; why is 21 cm line still visible?

6. What is a polytropic equation of state? Give examples of objects for which this is a very good approximation, and explain why it is.

7. What was the solar neutrino problem, and how was it resolved?

- Can neutrinos account for all of dark matter?
- If there was a 4th neutrino flavour, how could we detect it?
- Why is the first pp-chain (i.e. p+ + p+ -> 2-H + neutrino) not where we looked for neutrino signatures? (not energetic enough)

8. Why is nuclear fusion stable inside a main-sequence star? Under what conditions is nuclear fusion unstable? Give examples of actual objects.

- Can Main Sequence stars have unstable nuclear fusion?

9. Why do neutrons inside a neutron star not decay into protons and electrons?

10. What is the typical temperature of matter accreting on a star, a white dwarf, a neutron star, a stellar mass black hole, and a supermassive black hole? In what wavelength range would one best find examples of such sources?

- How does the accretion process work?
- If you don't assume a blackbody, and just dump a ton of material on a star/WD and it can't radiate away, what is the maximum temperature it can reach?

11. You don't usually need to cool down the detectors for short wavelength (e.g., X-ray) observations, but it's critical to cool down the detectors in long wavelength (e.g., far-IR) observations. Why is this, and why is it not necessary for radio observations?

12. Compare the S/N ratios between the following two cases where photon noise is dominant (assume an unresolved point source): [A] 1-minute exposure with a 10-m telescope; [B] 10- minute exposure with a 1-m telescope.

13. Describe linear and circular polarizations of electromagnetic waves and give examples of their relevance to astronomical observations.

14. What's the field of view of a 2K x 2K CCD camera on a 5-m telescope with f/16 focal ratio? The pixel size of the CCD is 20 micron. Now, let's bring this to a 10- m telescope with the same focal ratio. Explain

how the field of view changes on the 10-m telescope (compared to that of the 5-m telescope) based on the Etendue conservation rule.

- If you wanted a smaller FOV for the same size telescope what would you change (focal ratio)?

15. Sketch and give the equations for each of the following distributions: 1. Gaussian (Normal distribution); 2. Poisson distribution; 3. Log-normal distribution. Give two examples from astrophysics where each of these distributions apply.

16. You are trying to determine a flux from a CCD image using aperture photometry, measuring source(+sky) within a 5-pixel radius, and sky within a 20-25 pixel annulus. Assume you find 10000 electrons inside the aperture and 8100 electrons in the sky region, and that the flux calibration is good to 1%. What is the fractional precision of your measurement? (Ignore read noise.) More generally, describe how you propagate uncertainties, what assumptions you implicitly make, and how you might estimate errors if these assumptions do not hold.

17. Suppose you measure the brightness of a star ten times (in a regime where source- noise dominates. (1) How do you calculate the mean, median, and mode and standard deviation? (2) How can you tell if any points are outliers? Say some points are outliers, what do you do now (ie. how does this impact the calculation of the quantities in part 1)?

18. Suppose you do an imaging search for binaries for a sample of 50 stars, and that you find companions in 20 cases. What binary fraction do you infer? Suppose a binary- star fraction of 50% had been found previously for another sample (which was much larger, so you can ignore its uncertainty). Determine the likelihood that your result is consistent with that fraction.

19. What are the primary wavelength bands at which searches for gravitational waves are conducted? What techniques are used to search in each band? What are the sources of gravitational waves in each band? What can we learn from detections (or non-detections)?

20. Self-similarity is a useful idealization of many astrophysical systems. Explain what self-similarity means, when it works, and why it is so useful, and provide two examples from any field.

21. Explain why diffraction-limited detectors tend to have sidelobes, and how sidelobes can be suppressed in optical and radio observations.