Ph.D. Qualifying Examination
Department of Astronomy
May 27th, 2014
8:30 a.m. — 1:30 p.m.

Name: ___________________________

Student Number: _________________

The exam sheets are inside this envelope and are not fastened together. When you are finished, please put the questions and your answer sheets back in the envelope in the correct order. **Be sure the student number given to you by the proctor is on every page of your answers.**

Astronomy Program students **MUST** do the **FIRST TWO** problems and **SIX** more problems from the remaining **EIGHT**.

Astrophysics Program students **MUST** do **ONE** of the **FIRST TWO** problems and **FOUR** more problems from the remaining **EIGHT**. Astrophysics students must finish by **12:00 p.m.** (3.5 hours).

M.A. students must do **ONE** of the **FIRST TWO** problems and **THREE** more problems from the remaining **EIGHT**. M.A. students must finish by **11:00 a.m.** (2.5 hours).

PHYSICAL CONSTANTS

$c = 3.00 \times 10^{10}$ cm/s
$G = 6.67 \times 10^{-8}$ dyn cm^2/g^2
$h = 6.63 \times 10^{-27}$ erg s
$k = 1.38 \times 10^{-16}$ erg/K
$m_p = 1.67 \times 10^{-24}$ g
$a = 7.56 \times 10^{-15}$ erg cm^{-3} K^{-4}
$e = 4.80 \times 10^{-10}$ esu
$m_e = 9.11 \times 10^{-28}$ g
$\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} K^{-4} s^{-1}
$\sigma_T = 6.65 \times 10^{-25}$ cm^2
1 eV = 1.6×10^{-12} erg

$R_\odot = 6.96 \times 10^{10}$ cm
$M_\odot = 1.99 \times 10^{33}$ g
$L_\odot = 3.90 \times 10^{33}$ erg/s
A.U. = 1.50×10^{13} cm
1 yr = 3.16×10^7 sec
1 parsec = 3.09×10^{18} cm
$M_{V_\odot} = 4.83$ mag
$B.C._\odot = -0.07$ mag
$(B-V)_\odot = 0.64$ mag
$T_{eff_\odot} = 5770$ K
$M_E = 5.97 \times 10^{27}$ g
$R_E = 6.38 \times 10^8$ cm

REQUIRED: QUESTION 1 – Stellar Evolution

A) Describe in detail the evolution of a 15 solar mass star from the point at which it starts to collapse through to the end of its lifetime. In particular, state the primary energy source(s) present at each stage of its evolution. Trace that evolution on an H-R diagram. Give estimates of the amount of time spent in each stage, as well as for entire lifetime of the star. What spectral type would this star have while on the main sequence? Give as much detail as you can. [70 points]

B) What is the luminosity of the star in part (A) when it is on the main sequence, in solar units? Explain how this result was obtained. [30 points]

REQUIRED: QUESTION 2 – Galaxy luminosity functions

The figure on the next page shows the galaxy luminosity function for the Virgo cluster. The curve labeled "Total" gives the total number of galaxies of a given absolute magnitude, summed over all morphological types. Contributions to the total luminosity function coming from E, dE, Irr, S0 and Spiral galaxies are provided by the curves lying below the total curve. Only the S0 contribution is labeled.

Please include the page containing the figure (with your work shown) in your assembled answers.

A. Label each unlabeled curve with the appropriate galaxy type. [14 points]

B. The cluster luminosity function represents an integrated property; it gives no information on spatial distributions within a cluster. Describe any differences that are seen in the distribution of different morphological types within a cluster environment. [14 points]

C. Cluster luminosity functions are based on flux-limited observations of galaxies over a large volume of space. For these reasons, corrections must be applied to the analysis in order to correct for the Malmquist bias. This bias leads to the luminosity function being less well determined towards the right side of the figure below. Explain this bias in this case and why it leads to uncertainty. [14 points]

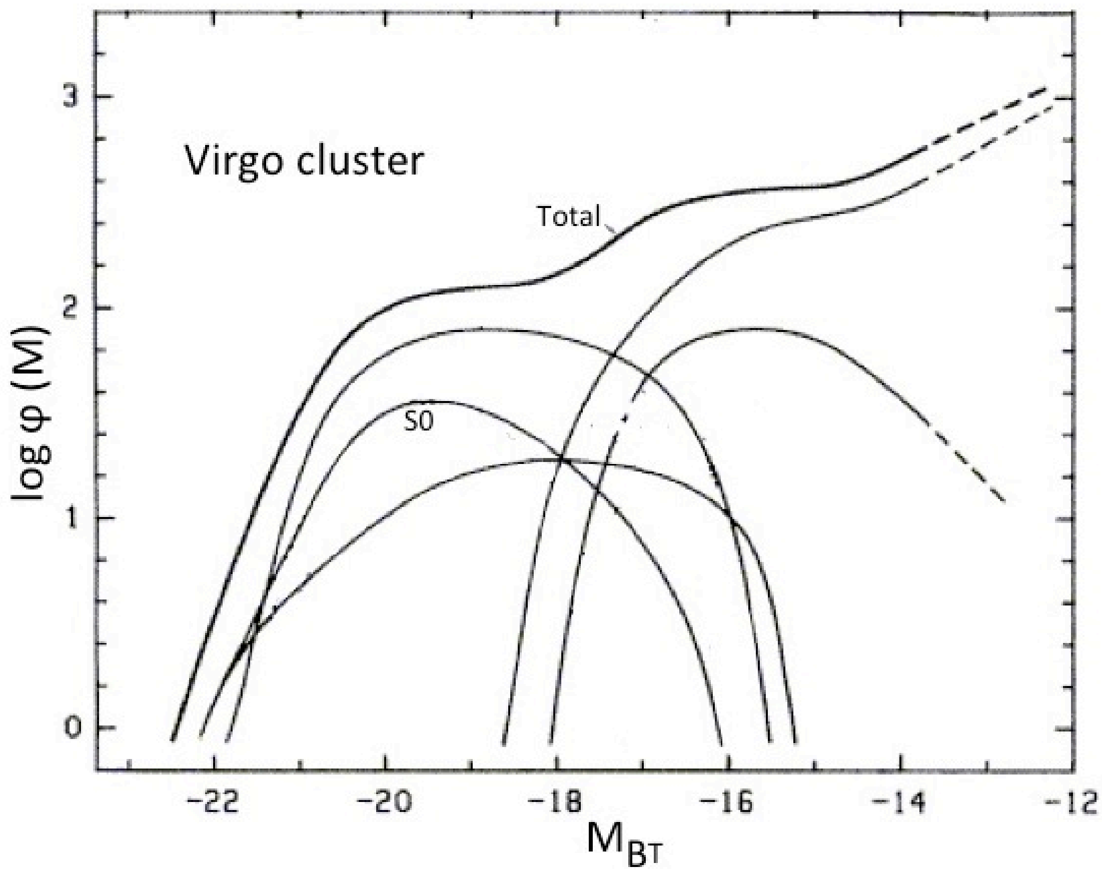
D. The total luminosity function rises over the full luminosity range of the figure. If the limiting flux on which the figure is based allowed for the x-axis to be extended to the right for an additional six magnitudes, what would you expect to happen to the "Total" curve? Explain. [14 points]

E. Assuming that the contributions to the total luminosity function for the Virgo cluster are typical of the universe as a whole, what is the most common type of galaxy? What are typical sizes and masses for this type galaxy? Explain how masses are determined for this type of galaxy. [15 points]

F. Again assuming that these individual contributions to the total luminosity function for the Virgo cluster are typical of the universe as a whole, what is the most common *bright* galaxy? What are typical sizes and masses for this type galaxy? Explain how masses are determined for this type of galaxy. [15 points]

G. Describe the frequency of different morphological types in the Local Group. How does this differ from that found for the Virgo cluster or other large clusters? Approximately how many galaxies are known to belong to the Local Group? What is the largest member of the group? [14 points]

Figure for Question 2 **Student Number ________.**



The Luminosity Function of Virgo cluster galaxies.

QUESTION 3: Stellar Atmospheres

A) What is meant by the “curve of growth” of an absorption line? Draw a schematic curve of growth with axes labeled. Name and explain the parts of the curve of growth and describe how the equivalent width of the absorption line varies as the abundance of the species in the stellar atmosphere is increased. [30 points]

B) Discuss what factors determine how strong a spectral line will be and explain why they play a role. Identify the parameter that will generally have the strongest effect on line strength and explain why this is. [30 points]

C) Describe the primary physical processes that create opacity in a star and explain the impact opacity has on the observed stellar spectrum. Then identify the dominant source of both a) continuous opacity and b) line absorption at visible wavelengths in the atmospheres of each of the stars listed below. For the line absorption, give several examples of the most prominent features that would be visible: [40 points]

i) an O star
ii) a main sequence A star
iii) the sun
iv) an M giant star

QUESTION 4: Neutrino flux

Estimate the number of neutrinos going through your body every second. Explain very clearly all your assumptions and chain of reasoning. [100 points]

QUESTION 5: Binary Star Systems

The M5Ve dwarf eclipsing binary CU Cnc has a period of 2.77 days, with a semi-major axis of 0.017 AU. The parallax of CU Cnc is 90. 37 ± 8.22 mas, and its proper motion is -254.94 mas yr^{-1} in RA and -94.98 mas yr^{-1} in declination (± 10.02 and 5.51 respectively). CU Cnc has a V magnitude of 12.05 and a K magnitude of 6.603.

A radial velocity study indicates that the amplitude of radial velocity variation for the primary in the system is K_1 = 68.09 km s^{-1}, and the amplitude of the secondary is K_2 = 74.14 km s^{-1}.

A) What are the masses of the two components of CU Cnc? [25 points]

A second variable M dwarf, CV Cnc, with a spectral type of M4.0V, is located just 10.1" away. CV Cnc has a parallax of 78.1 ± 5.7 mas and a proper motion of -223 mas yr^{-1} in RA and -123 mas yr^{-1} in dec. The V magnitude of CV Cnc is 14.83 and its K magnitude is 7.72.

B) If CU Cnc and CV Cnc are in a binary system, what is their physical separation? [25 points]

C) Assuming that CV Cnc is at apastron, what is the approximate period of its orbit with CU Cnc? [25 points]

D) Using the data provided, give arguments for and/or against the hypothesis that CV Cnc and CU Cnc are gravitationally bound. [25 points]

QUESTION 6: Dynamics of Star Clusters

A) The gravitational potentials of a Navarro-Frenk-White model is

$$\Phi(r) = -4\pi G\rho_o\, a^2 \, \frac{\ln(1 + r/a)}{(r/a)} \, .$$

Indicate whether this model has a finite mass (show your calculations) and calculate the scaling with r of its circular speed at large radii. [25 points]

B) Sketch the time evolution of the Lagrangian radii of a star cluster, identify the point of core collapse, and discuss the role of binary stars in this and in the post-core collapse phase. Discuss the difference between *hard* and *soft* binaries, the key parameter used to classify a binary as *hard* or *soft*, and their different evolution in a star cluster. [25 points]

C) Discuss at least one possible dynamical mechanism for the formation of binary stars in star clusters. [15 points]

D) Discuss the meaning of tidal radius of a star cluster and its scaling with the cluster mass and distance from the center of the host galaxy (you can assume a host galaxy characterized by a constant circular velocity). [35 points]

QUESTION 7: Stellar Photometry

Suppose your goal is to perform BV photometry of three specific stars: you have measured the stars' instrumental magnitudes in a set of images and you wish to calculate the calibrated V magnitude and B-V color of each star. Your data set includes both images of the target stars and images of photometric standard stars. Below are listed the photometric calibration coefficients you have derived from your data, as well as the instrumental magnitudes you have measured for the three stars.

Instrumental Magnitude	**Star 1**	**Star 2**	**Star 3**
b_i	-7.97	-7.62	-7.42
v_i	-7.02	-6.99	-7.47

Atmospheric extinction coefficients: $k_B = 0.21$ $k_V = 0.14$

Color transformation coefficients:

For mag. equation (ε) = 0.05 For color equation (μ_{bv}) = 0.95

Zero point constants:

For mag. equation (ζ_v) = 19.50 For color equation (ζ_{bv}) = 0.70

A) Write down equations that describe the atmospheric extinction corrections for the B and V instrumental magnitudes. Define all symbols used. Use these equations and the data provided to compute the extinction-corrected instrumental magnitudes (b_0 and v_0) for all three stars. Assume all data were obtained at an airmass of 1.50. [15 points]

B) Write down equations that describe the conversion from instrumental quantities to calibrated V magnitude and B-V color. Define all symbols used, and explain their purpose in the equations. What do the various coefficients correct for? Finally, use these equations and the data to compute V and B—V for each of the three target stars. [30 points]

C) Give your best estimates for both the spectral type and the effective temperature of these three stars. Also specify which of the three stars will have the strongest Balmer lines, and why. Fully explain/justify your answers. [30 points]

D) Assume that Star 1 has a V-band photometric measurement error of 0.01 magnitude. Calculate the V magnitude of a star with a signal-to-noise ratio of ~20 appearing in the same image as Star 3. (Ignore all sources of error except photon-counting errors, and assume the CCD you are using has a linear response to incoming photon flux.) [25 points]

QUESTION 8: ALMA Observations of AGNs

When complete, ALMA will consist of fifty 12m antennas located on the high altitude plains above San Pedro, Chile. This year, during Cycle 2, thirty-four telescopes will be distributed in the array with1.5km as the most distant separation between antennas and the closest antennas separated by only 15m. The principles of millimeter astronomy are identical to optical astronomy, but the nomenclature is sometimes different. For example, optical astronomers refer to the 'point spread function' while radio/mm astronomers refer to the 'beam.'

A) Calculate the theoretical 'primary beam' (or resolution) of a single ALMA antenna when operated at 115 GHz (CO 1-0 at low redshift). [10 points]

B) Calculate the theoretical maximum and minimum spatial scales over which the array is sensitive when conducting continuum observations in band 6 (300 GHz). [20 points]

C) Consider 300 GHz continuum monitoring observations of a blazar identified at redshift 3.7. [40 points]

   i. What is the rest-frame wavelength of these observations and what is the likely dominant source of continuum emission at these wavelengths?
   ii. If the blazar goes through fluctuations in brightness that last 6 days as seen from Earth, how long does this fluctuation last as measured within the host galaxy (use the concept of cosmological time dilation).
   iii. What is the maximum size of the region from which this blazar emits energy? If optical observations indicate emission lines with typical linewidths of 15000 km/s, derive an estimate of the mass of the central object (in solar masses). Show your work.
   iv. What is the Schwarzschild radius of this object? Based on your answers, is the central object likely to be a black hole?

D) Draw a schematic that illustrates AGN unification models. In complete sentences, describe the observed differences in major classes of AGN and explain how this schematic "unifies" AGN models. [20 points]

E) Referencing data obtained at any wavelength, describe the scientific evidence for a Black Hole at the center of our galaxy. [10 points]

QUESTION 9: Cosmology

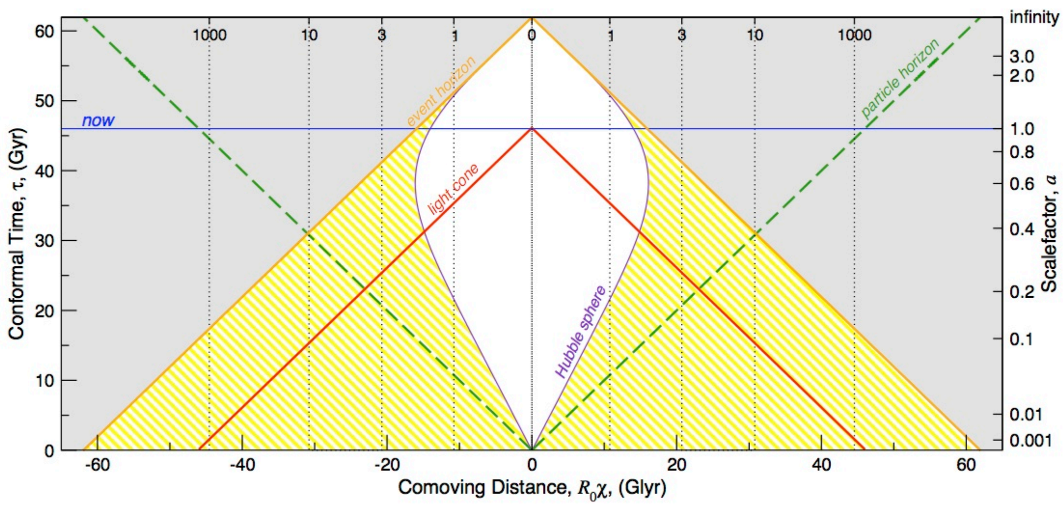
A) Hubble's Law

(i) State Hubble's law for local galaxies in the Hubble flow. Define the terms/units. How is the method of "standard candles" used to determine the Hubble constant? [20 Points]

(ii) What is the Cosmological Principle? How is the Cosmological Principle used in the derivation of Hubble's law? Is there any convincing evidence that the Cosmological Principle is valid? Explain. [20 Points]

B) Horizon problem

(i) What is the horizon problem? Illustrate the horizon problem using the space-time diagram for our ΛCDM universe. [15 Points]



(ii) How does inflation solve the horizon problem? Sketch how the space-time diagram above would be modified for inflation and how this solves the horizon problem. [15 Points]

C) Solve Friedmann's equation (below) for the early universe. Explain the assumptions you use to simplify Friedmann's equation. [30 Points]

$$H^2(R) = H_0^2\,[\Omega_m^0(R_0/R)^3 + \Omega_r^0(R_0/R)^4 + \Omega_\Lambda^0 + (1-\Omega_T^0)(R_0/R)^2]$$

QUESTION 10: Basic components of the Milky Way

This problem gives you an opportunity to describe what we know and don't yet know about the Milky Way galaxy.

A) Provide a description of the major stellar and non-stellar structural components of the Milky Way galaxy, characterizing them in terms of any distinguishing properties that you feel are important. Include, at a minimum, a description in terms of the properties listed below, as appropriate to that component. Begin your answer with a clear list of the principal components that make up the Galaxy. Then use the properties below to compare and contrast the characteristics of these components. Feel free to use tables or sketches to supplement your written answer, and be as quantitative as possible. [90 points]

- spatial or density distributions
- total mass
- kinematics or orbital properties
- overall metallicities
- detailed chemical abundances
- age(s)

B) Select one of these Galactic components and briefly describe a current controversy in the field or an area where our knowledge is still lacking. [10 points]