Exam information	
Course code and title	PHYS 3080 - Extragalactic Astrophysics and Cosmology
Semester	Semester 1, 2022
Exam type	Online, non-invigilated, end-of-semester examination
Exam technology	File upload to Blackboard Assignment
Exam date and time	Your examination will begin at the time specified in your personal examination timetable. If you commence your examination after this time, the end for your examination does NOT change. The total time for your examination from the scheduled starting time will be: 2 hours 10 minutes (including 10 minutes reading time during which you should read the exam paper and plan your responses to the questions). A 15-minute submission period is available for submitting your examination after the allowed time shown above. If your examination is submitted after this period, late penalties will be applied unless you can demonstrate that there were problems with the system and/or process that were beyond your control.
Exam window	You must commence your exam at the time listed in your personalised timetable. You have from the start date/time to the end date/time listed in which you must complete your exam.
Permitted materials	This is an open book exam – any material permitted.
Recommended materials	Ensure the following materials are available during the exam: UQ approved calculator; bilingual dictionary; phone/camera/scanner
Instructions	You will need to download the question paper included within the Blackboard Test. Once you have completed the exam, upload the completed exam answers file to the Blackboard assignment submission link. You may submit multiple times, but only the last uploaded file will be graded. You can print the question paper and write on that paper or write your answers on blank paper (clearly label your solutions so that it is clear which problem it is a solution to) or annotate an electronic file on a suitable device.
Who to contact	Given the nature of this examination, responding to student queries and/or relaying corrections to exam content during the exam may not be feasible. If you have any concerns or queries about a particular question or need to make any assumptions to answer the question, state these at the start of your solution to that question. You may also include queries you may have made with respect to a particular question, should you have been able to 'raise your hand' in an examination-type setting. If you experience any interruptions to your examination, please collect evidence of the interruption (e.g. photographs, screenshots or emails). If you experience any issues during the examination, contact ONLY the Library AskUs service for advice as soon as practicable: **Chat:** support.my.uq.edu.au/app/chat/chat_launch_lib

	Phone: +61 7 3506 2615 **Email:** examsupport@library.uq.edu.au You should also ask for an email documenting the advice provided so you can provide this as evidence for a late submission.
Late or incomplete submissions	In the event of a **late submission**, you will be required to submit evidence that you completed the assessment in the time allowed. This will also apply if there is an **error in your submission** (e.g. corrupt file, missing pages, poor quality scan). We **strongly recommend** you use a phone camera to take time-stamped photos (or a video) of every page of your paper during the time allowed (even if you submit on time). If you submit your paper after the due time, then you should send details to SMP Exams (exams.smp@uq.edu.au) as soon as possible after the end of the time allowed. Include an explanation of why you submitted late (with any evidence of technical issues) AND time-stamped images of every page of your paper (eg screen shot from your phone showing both the image and the time at which it was taken).
Important exam condition information	Academic integrity is a core value of the UQ community and as such the highest standards of academic integrity apply to all examinations, whether undertaken in-person or online. This means: • You are permitted to refer to the allowed resources for this exam, but you cannot cut-and-paste material other than your own work as answers. • You are not permitted to consult any other person – whether directly, online, or through any other means – about any aspect of this examination during the period that it is available. • If it is found that you have given or sought outside assistance with this examination, then that will be deemed to be cheating. If you submit your online exam after the end of your specified reading time, duration, and 15 minutes submission time, the following penalties will be applied to your final examination score for late submission: • Less than 5 minutes – 5% penalty • From 5 minutes to less than 15 minutes – 20% penalty • More than 15 minutes – 100% penalty These penalties will be applied to all online exams unless there is sufficient evidence of problems with the system and/or process that were beyond your control. Undertaking this online exam deems your commitment to UQ's academic integrity pledge as summarised in the following declaration: *"I certify that I have completed this examination in an honest, fair and trustworthy manner, that my submitted answers are entirely my own work, and that I have neither given nor received any unauthorised assistance on this examination".*

Question 1 **[Total 10 marks]**

a) The rotation curves of most spiral galaxies are flat throughout the disks, with a typical constant angular velocity of $v = 200$ km/s at radii between 4 kpc $< R <$12 kpc.

i. Assume (naïvely) that the spiral arms are material. Calculate the time until the outer stars at R =12 kpc have gained three orbits on the inner stars at $R = 4$ kpc and the spiral arm pattern thus becomes difficult to distinguish. Show your working. [2 marks]

ii. Spiral arms are nearly ubiquitous in disk galaxies (10% are grand design spirals and 60% are multiple arm galaxies), and the typical age of a disk galaxy is >10 Gyr. Compare your answer in i) to these two observations. What can you conclude about the spiral arms? [1 mark]

iii. Briefly and qualitatively explain how Lin-Shu density theory solves the winding problem and explains the appearance of the spiral arms. [2 marks]

b) The Tully-Fisher relation and the Faber-Jackson relation are sometimes unified in e.g. the $S_{0.5}$ relation, $S_{0.5} = \sqrt{0.5V_{rot}^2 + \sigma^2}$. Barat et al. (2020) found $\log M_* = 2.58 \log S_{0.5} + 5.16$ for the stellar mass of a galaxy, with low-mass dwarf galaxies below $M_* < 10^{8.3} M_\odot$ falling below the relation at constant $S_{0.5} = 10^{1.2}$ independent of stellar mass.

i. Suggest a reason for why dwarf galaxies fall below the $S_{0.5}$ relation. [1 mark]

ii. Consider a dwarf galaxy of $M_* = 10^6 M_\odot$ and $S_{0.5} = 10^{1.2}$. If using the $S_{0.5}$ relation to estimate its stellar mass, one would find $M_* = 10^{8.3} M_\odot$. This error would then affect the predicted magnitude. Use the relation between stellar mass and magnitude, $\log M_* = 1.15 - 0.4 M_i$, to show that the difference between its actual magnitude and the magnitude predicted by the $S_{0.5}$ relation is 5.8 magnitudes. [2 marks]

iii. Thus calculate the error in distance for such a dwarf at 10 Mpc if mass is estimated using its observed $S_{0.5}$ parameter and the mass magnitude relation. [2 marks]

Question 2 **[Total 10 marks]**

In cosmological simulations it is often found that the density $\rho(r)$ of dark matter in galaxies can be described by a so-called Navarro, Frenk and White (NFW) profile:

$$\rho(r) = \frac{\rho_0}{\frac{r}{a}\left(1 + \frac{r^2}{a^2}\right)}$$

where r is the distance from the centre of the galaxy, ρ_0 is a constant and a is the so-called scale radius.

a) How does the density depend on radius r for $r \ll a$ and $r \gg a$? Create a sketch showing how the density depends on radius for an NFW profile. [2 marks]

b) Show that the total mass of a dark matter halo is diverging in an NFW profile if $r \to \infty$. How must the true dark matter density in galaxies depend on radius for large radii so that this does not happen? [3 marks]

c) How does the circular velocity depend on radius for $r \ll a$ and $r \gg a$? Draw a sketch of the derived rotation curve and compare with the observed behaviour of rotation curves in galaxies. [3 marks]

d) Simulations show that Milky Way like galaxies have typical scale radii $a = 5$ kpc and densities ρ_0 = 1.5 M_{Sun}/pc^3. The Sun is at a distance of $R = 8.2$ kpc from the centre of the Milky Way. How large is the dark matter density in the vicinity of the Sun (both in units of M_{Sun}/pc^3 and kg/m^3)? [2 marks]

Question 3 **[Total 10 marks]**

Write a short essay on **ONE** of the following three topics. Your essay must not exceed two pages including any diagrams. There are **10 marks** available for your essay. Of these marks, two will be awarded for the overall construction of your essay, including grammar.

a) Describe the processes behind the different types of galaxy mergers. Ensure that your answer addresses i) dynamical friction, ii) size ratio & morphology, iii) gas fraction and angular momentum, and iv) the Hubble Tuning Fork vs. the ATLAS3D comb.

b) Can dark energy and dark matter be explained by a variation in our theory of gravity? Give examples of observational evidence for your answer.

c) Describe the important steps in the thermal history of the universe. Include at least five stages and/or major transitions. In your description consider important general features like the temperature of the universe, the composition of the universe, and the competition between pressure and gravity.

Question 4 **[Total 10 marks]**

The Friedmann equation can be written:

$$H^2(a) = H_0^2 \sum_i \Omega_i a^{-3(1+w_i)} \quad .$$

a) What do the w_i represent in this equation? How do they relate to pressure and density? [1 mark]

b) What do the Ω_i refer to? How do they relate to the critical density? [1 mark]

c) Name three of the different possibilities for Ω_i that might appear in that sum, and what value of w_i does each one of them correspond to? [1 mark]

d) Assume you live in a flat universe with matter density 0.3 times the critical density with the only other component of the universe being dark energy in the form of a cosmological constant. Expand the equation above to show how the Hubble parameter changes with redshift in such a universe. [3 marks]

e) In a flat, matter-dominated universe, calculate what the scale factor would have been when the universe was half its present age. [4 marks]

Question 5 **[Total 10 marks]**

a) Assume the epoch of matter-radiation equality occurred at $z \sim 3600$ and an age of 60 kyr. What was the temperature of the universe at that time? [2 marks]

b) What was the energy of a typical particle at the time of matter-radiation equality in eV? [2 marks]

c) During inflation, is it the rapid expansion of the universe, or the rapid acceleration of the universe that solves the horizon and flatness problems? Explain why. [2 marks]

d) Draw a BAO correlation function and power spectrum. Mark on them the BAO scale. Make sure you label your axes. [2 marks]

e) How is the curvature of the universe determined using measurements of the Cosmic Microwave Background (CMB)? [2 marks]

CONSTANTS

Quantity	*Symbol*	*Value*	*Units*
1 arc second	1”	4.85×10^{-6}	radians
astronomical unit	AU	1.5×10^{11}	m
light year	ly	9.46×10^{15}	m
year	yr	3.15×10^{7}	s
parsec	pc	3.26	ly
parsec	pc	206265	AU
parsec	pc	3.09×10^{16}	m
Hubble constant	H_0	70	km s^{-1} Mpc^{-1}
Hubble constant.	H_0	0.072	Gyr^{-1}
CMB temperature	T_{CMB}	2.725	K
Solar abs. mag. (Bolometric)	M_{Sun}	4.74	
Solar abs. mag. (B band)	$M_{B,Sun}$	5.47	
Solar apparent magnitude	m_{Sun}	-26.73	
Solar radius	$R_\odot$	6.96×10^{8}	m
Solar mass	$M_\odot$	1.98×10^{30}	kg
Solar luminosity	$L_\odot$	3.84×10^{26}	W
Jovian mass	M_{Jupiter}	1.89×10^{27}	kg
Terrestrial mass	M_{Earth}	5.97×10^{24}	kg
Terrestrial radius	R_{Earth}	6.38×10^{6}	m
Milky way rotation velocity	v_{rot}	220	km s^{-1}
Speed of light	c	2.99792×10^{8}	m s^{-1}
Planck’s constant	h	6.63×10^{-34}	J s
Planck’s constant	$\hbar$	1.05×10^{-34}	J s
Boltzmann constant	k_B	1.38×10^{-23}	J K^{-1}
Boltzmann constant	k_B	8.62×10^{-5}	eV K^{-1}
Stefan-Boltzmann constant	σ	5.67×10^{-8}	J m^{-2} s^{-1} K^{-4}
Rydberg constant	R_H	1.10×10^{7}	m^{-1}
Electron Volt	eV	1.60×10^{-19}	J
Electron mass	m_e	9.11×10^{-31}	kg
Hydrogen mass	m_H	1.67×10^{-27}	kg
Gravitational constant	G	6.67×10^{-11}	m^3 kg^{-1} s^{-2}
Gravitational constant	G	0.0043	pc (km/s)^2/M$_\odot$

$$d(\text{pc}) = 1/p \quad (\text{arcsec})$$
$$m - M = 5\log_{10}\left(\frac{d}{10\text{pc}}\right)$$
$$M - M_\odot = -2.5\log_{10}\left(\frac{L}{L_\odot}\right)$$
$$L = 0.1\dot{M}c^2$$

$$v = \sqrt{\frac{GM(<R)}{R}}$$
$$\vec{F} = -\frac{Gm_1m_2}{|r|^3}\vec{r}$$
$$F = mv^2/r$$
$$M(<R) = 4\pi\int_0^R \rho(r)r^2 dr$$
$$z = \frac{\lambda_1 - \lambda_0}{\lambda_0} = \frac{1}{a} - 1$$
$$a = \frac{R}{R_0} = \frac{1}{1+z}$$
$$D = R\chi$$
$$v = HD$$
$$H = \frac{\dot{R}}{R}$$
$$H^2 = H_0^2\sum_i \Omega_i a^{-3(1+w_i)}$$
$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2}$$
$$\rho_{\text{crit},0} = \frac{3H_0^2}{8\pi G}$$
$$\Omega = \rho/\rho_{\text{crit}}$$
$$\rho_\Lambda = \frac{\Lambda}{8\pi G}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\sum \Omega_i a^{-3(1+w_i)}$$
$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a$$

$$ds^2 = -c^2dt^2 + R^2(t)\left[d\chi^2 + S_k^2(\chi)(d\theta^2 + \sin^2\theta d\phi^2)\right]$$
$$S_k(\chi) = \sin\chi\,(\text{closed}), \chi\,(\text{flat}), \sinh\chi\,(\text{open})$$
$$T_{then} = T_{now}(1+z)$$
$$T_{\text{moving}} = \frac{T_{\text{rest}}\sqrt{1 - v^2/c^2}}{1 - (v/c)\cos\theta} \approx T_{\text{rest}}\left(1 + \frac{v}{c}\cos\theta\right)$$
$$t_* \approx \frac{1}{nv(4\pi R^2)}$$
$$t_* \approx 5\times10^{10}\text{Gyr}\left(\frac{R}{R_\odot}\right)^{-2}\left(\frac{v}{30\text{km s}^{-1}}\right)^{-1}\left(\frac{n}{0.1\text{pc}^{-3}}\right)$$
$$\frac{d^2R}{dt^2} = -\frac{4\pi GR}{3}\left(\rho + \frac{3p}{c}\right)$$
$$\dot{M}_E = 2\frac{M_\odot}{yr}\left(\frac{\eta}{0.1}\right)^{-1}\left(\frac{M_{BH}}{10^8 M_\odot}\right)$$
$$L_E = 3.3\cdot10^{12}L_\odot\left(\frac{M_{BH}}{10^8M_\odot}\right)$$
$$\frac{d^2R}{dt^2} = -\frac{4\pi GR}{3}\left(\rho + \frac{3p}{c}\right)$$
$$\rho_i = \rho_{i,0}a^{-3(1+w_i)}$$
$$\Omega_i = \Omega_{i,0}a^{-3(1+w_i)}$$
$$w = \frac{p}{\rho c^2}$$
$$w_R = 1/3$$
$$w_M = 0$$
$$w_K = -1/3$$
$$w_\Lambda = -1$$
$$\int_{t_1}^{t_2} dt = \int_{a_1}^{a_2}\frac{da}{Ha}$$
$$\epsilon = k_BT$$
$$aT = \left(\frac{11}{4}\right)^{1/3} aT_\nu$$
$$Y = \frac{4n_{\text{He}}}{4n_{\text{He}} + n_H}$$
$$\int dt = \int\frac{da}{\dot{a}}$$
$$\int d\chi = c\int\frac{dz}{H(z)}$$

END OF EXAMINATION