Australian National University

Venue ____________________

Student Number |__|__|__|__|__|__|__|__|

EXAMINATION

Semester 2 - End of Semester, 2018

ASTR1001 Semester 2 Astrophysics

This paper is for ANU students.

Examination Duration: 180 minutes

Reading Time: 15 minutes

Exam Conditions:

Central Examination

Materials Permitted in the Exam Venue:

One A4 page with notes on both sides. Calculator (programmable is OK). Unannotated paper-based dictionary (no approval required),

(No electronic aids are permitted e.g. laptops, phones)

Materials to Be Supplied To Students:

1 x 20 page plain

Instructions to Students:

Complete all nine questions. They are all worth equal marks.

A formula sheet and a list of useful constants and definitions is at the end of the exam paper.

Question 1

Question 2

Question 3

Question 4

Question 5

Question 6

Question 7

Question 8

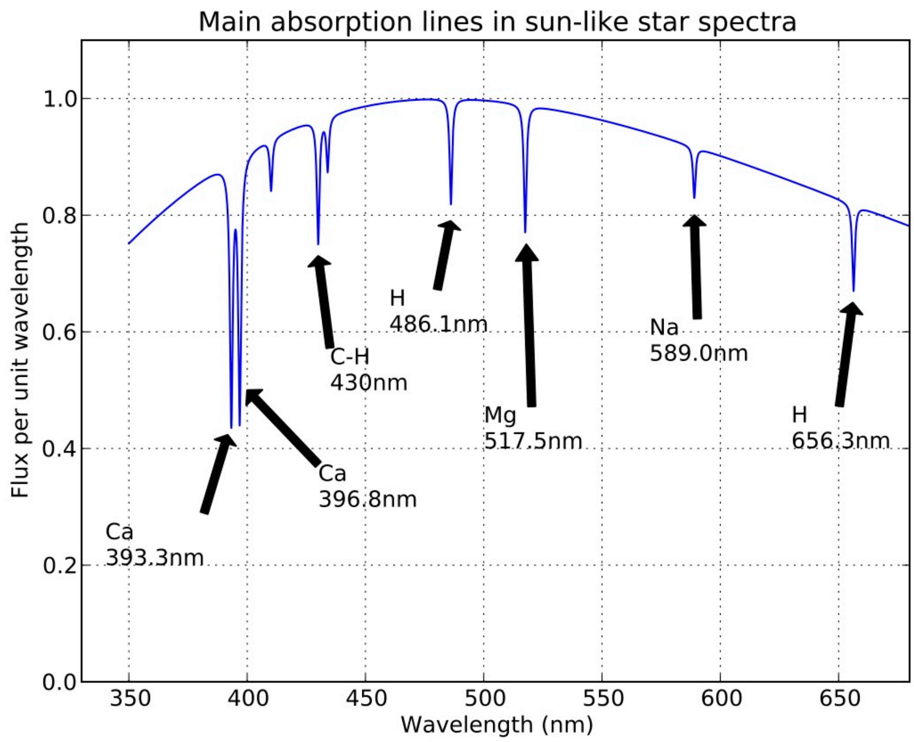
Question 9

END OF EXAMINATION

Equations, Physical constants and other data

Speed of light	$c=3\times10^{8}$ m s^{-1}
Universal gravitational constant	6.67×10^{-11} N m^{2} kg^{-2}
Magnitude of charge on electron	$e = 1.6\times10^{-19}$ C
Stefan-Boltzmann constant	$\sigma=5.67\times10^{-8}$ W m^{-2} K^{-4}.
Mass of electron	9.11×10^{-31} kg
Mass of proton	1.67×10^{-27} kg
Planck's constant	$h = 6.636\times10^{-34}$ Js
Volume of a sphere, radius R	$(4/3)\ \pi R^{3}$
Surface area of a sphere, radius R	$4\pi R^{2}$
Radius of Earth	6400 km
Mass of Earth	6×10^{24} kg
Mass of Jupiter	$1.898\text{x}10^{27}$ kg
Distance of Earth from Sun (AU)	1.5×10^{11}m.
Light year	9.5×10^{15} m
Parsec	3.1×10^{16} m
Solar Mass	2.0×10^{30} kg
Solar Radius	695700 km
Solar luminosity	$3.83\text{x}10^{26}$ W
Thompson cross-section:	$\sigma_T = 6.7\times10^{-29}\,m^2$

One arc-minutes = 1/60 degrees. One arc-second = 1/60 arc-minutes. One radian is $\frac{180}{\pi}$ degrees.



Newton's Law of Gravity: $F = \frac{GMm}{r^2}$

Doppler Effect: $\frac{v}{c} \approx \frac{\Delta\lambda}{\lambda}$

Redshift: $z = \frac{\lambda - \lambda_0}{\lambda_0}$

Centripetal Force: $F = \frac{mv^2}{r}$

Distance of planet from star: $r = \sqrt[3]{\frac{GM_* P^2}{4\pi^2}}$

Mass of radial velocity planet: $\frac{m_p}{m_*} = \frac{v_* P}{2\pi r}$

Stefan-Boltzmann Equation: $L = A\sigma T^4$

Wien Displacement Law: $\lambda = \frac{0.0029}{T} m$

Inverse Square Law: $f = \frac{L}{4\pi D^2}$

Small-angle approximation: $r = \theta D$ for object of size r, distance D and angle θ radians.

Uncertainty Principle: $\Delta x . \Delta p \geq \frac{h}{4\pi}$

Hubble Law: v = H_0 D

Reflex motion or transit: distance to planet: $r = \sqrt[3]{\frac{GM_* P^2}{4\pi^2}}$

Reflex Motion: velocity of star: $v_* = \frac{2\pi r}{P} \frac{M_p}{M_*}$

Eddington Limit: $L_E = \frac{4\pi G M_{\mathrm{star}} m_{\mathrm{proton}} c}{\sigma_T}$

SI Prefixes:

- Giga = 10^9
- Mega = 10^6
- Kilo = 10^3
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Australian National University

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PRACTICE EXAMINATION

Semester 1 - End of Semester, 2017

ASTR1001_Semester 1 Astrophysics

This paper is for ANU and TU Delft students.

Examination Duration:	180 minutes
Reading Time:	15 minutes

Exam Conditions:

Central Examination

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Instructions To Students:

Complete all six questions.

A formula sheet and a list of useful constants and definitions is at the end of the exam paper.

Question 1

Imagine that you are studying an edge-on galaxy that is at a distance of ten mega-parsecs from you. The galaxy has an apparent radius of 4.4 arcminutes.

A) What is the actual radius of this galaxy, in kilo-parsecs? **(3 marks)**
B) You take a spectrum of the centre of the galaxy, and see the H-alpha absorption line of hydrogen at a wavelength of 657.8 nm. The laboratory wavelength of this line is 656.3nm. What is the redshift of the galaxy? **(2 marks)**
C) You now take spectra of both edges of the galaxy. At one edge, the absorption line is at 658.31 nm, while at the other edge of the galaxy, the absorption line is a 657.35 nm. How fast is the galaxy rotating? **(5 marks)**
D) Balance centrifugal force against gravity and hence calculate the mass of the galaxy (in solar masses)? **(10 marks)**

Question 2

Fermi's paradox is a famous argument that says that life in space must be rare, because if it was common, Earth would have been colonised by aliens a long time ago.

Carefully explain the argument. Do you think it is valid? Explain your reasoning.

(20 marks)

Question 3

Imagine that you have been monitoring the apparent brightness of a sun-like star (a star with the same radius, mass and luminosity as our Sun). The observed brightness shows regular dips, due to transits of a planet which is orbiting the star.

The dips occur every 11.2 days. During each dip, the apparent flux from the star decreases by 0.32%.

A) Deduce as much as you can about the planet and its orbit. **(10 marks)**
B) By balancing the incoming and outgoing radiation, estimate the temperature of the planet **(10 marks)**

Question 4

Directly imaging exoplanets is very challenging.

A) Why is it so hard to image exoplanets? Carefully explain why telescopes have trouble imaging exoplanets. **(10 marks)**
B) Despite this, some exoplanets have now been imaged. Explain how this is achieved. **(10 marks)**

Question 5

Imagine that you have detected a bright blue dot in the centre of a distant galaxy – a galaxy 10^9 light years distant. You measure a flux from this blue dot of 3.0×10^{-15} W m^{-2}, and its spectrum is a perfect black body, peaking in the far ultraviolet, at a wavelength of 97 nm. The blue dot is too small to resolve with your telescope. The blue dot is constantly changing in brightness with a random pattern – it typically takes about a day to significantly change in brightness.

A) What is the luminosity of this blue dot? **(2 marks)**
B) What is the temperature of the blue dot? **(2 marks)**
C) Use two different methods to estimate the size of the blue dot. **(8 marks)**
D) Use the Eddington limit to place a limit on the mass of the blue dot. **(4 marks)**
E) Based on your answers to the previous questions, what do you think this blue dot might be? Explain your reasoning. **(4 marks)**

Question 6

Describe and explain the observational evidence for dark energy, and how it varies with redshift.

(20 marks)

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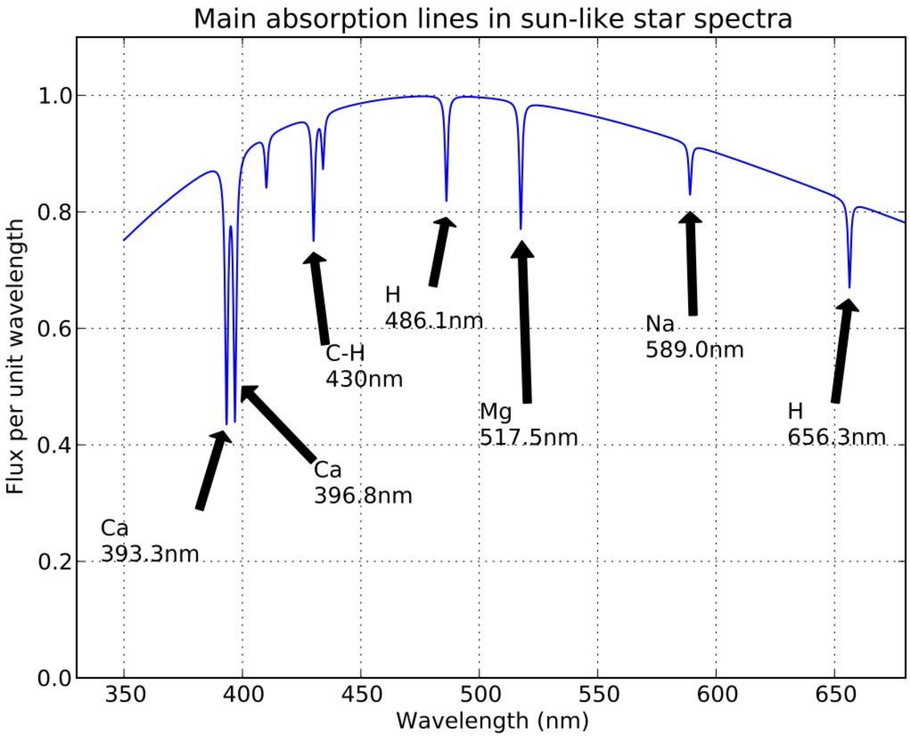

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Astro Exam Answers

Question 1

A) $r = D\theta = 10\times10^{6}\times3.1\times10^{16}\left(4.4\dfrac{\pi}{180*60}\right) = 3.97\times10^{20}m = 12800kpc$

B) $z = \dfrac{\Delta\lambda}{\lambda_0} = \dfrac{657.8-656.3}{656.3} = 0.0023$

C) Doppler effect equation says that $\dfrac{v}{c} = \dfrac{\Delta\lambda}{\lambda} = \dfrac{658.31-657.35}{657.35} = 0.00078$ and similarly from the other side. So the rotational speed is 0.00078x300000=234 km/s.

D) Balance centrifugal force against gravity:

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

Rearrange –

$$M = \frac{v^2 r}{G} = \frac{234000^2\times3.97\times10^{20}}{6.67\times10^{-11}} = 3.26\times10^{41}kg = 1.6\times10^{11}\text{solar masses}$$

Question 2

You need to compare the typical time needed to travel across the galaxy to the time for intelligent life to evolve. If the travel time is much shorter, you'd expect whichever species evolved first to spread before the later ones have a chance to evolve.

Even at 0.1% of the speed of light, spreading around the galaxy would take only ~ 10 million years, which is much less than evolutionary timescales (~ billions of years). So if a large fraction of the 10^{11} stars in our galaxy hosted intelligent life, we should certainly have been visited and colonised long since.

Not totally convincing because it assumes that species stay intelligent for tens of millions of years, and are interested in spreading around and colonising the galaxy. But it could be that most species destroy themselves or have some sort of "prime directive".

Question 3

From the period, use

$$r = \sqrt[3]{\frac{GM_*P^2}{4\pi^2}} = \sqrt[3]{\frac{6.67\times10^{-11}\times2\times10^{30}\times(11.2\times24\times3600)^2}{4\pi^2}} = 1.47\times10^{10}m \sim 0.1AU$$

As the dip is 0.32%, the area of the planet must be 0.32% of the area of the star. So

$$\frac{\pi r^2}{\pi R^2} = \frac{0.32}{100}$$

Rearranging, we find that $r = R\sqrt{\dfrac{0.32}{100}} = R\times0.0566 = 39355km$

So it's a big planet and pretty close in.

We can't work out the mass and density without any radial velocity data.

We can estimate the equilibrium temperature. By balancing heat out and heat in.

$$f = \frac{L}{4\pi D^2} = \frac{3.83\times10^{26}}{4\pi(1.47\times10^{10})^2} = 1.4\times10^5 Wm^{-2}$$

Incident heat if the planet is perfectly reflective is this times the cross-sectional area πr^2

Heat radiated is $A\sigma T^4 = 4\pi r^2 \sigma T^4$

Set them equal and you get $4\pi r^2 \sigma T^4 = \pi r^2 f$

Rearranging,

$$T = \sqrt[4]{\frac{f}{4\sigma}} = 886K$$

Question 4

A) It's hard to image exoplanets because the light from them is drowned out by light from the background star. This wouldn't be a problem if all the light in a telescope went where it was supposed to go, but in practice some of it goes in the wrong direction, due to atmospheric seeing, imperfections in the optics, and diffraction.

B) Adaptive optics can remove the effect of atmospheric seeing. Angular differential imaging can separate out the speckles due to telescope imperfections from the planet. Working at IR wavelengths and aiming at very young planets greatly increases the relative brightness of the planet.

Question 5

A) Use the inverse square law – $L=3.4\times10^{36}W$

B) Use the Wien displacement law – T~30,800K

C) Method 1 – if it varies in a day it can't be much more than a light day across – i.e. $24\times3600\times3.0\times10^8=2.6\times10^{13}$m across. Method two – use the Stefan-Boltzmann equation to get the luminosity from the known temperature and unknown area – so

$$A= r = \sqrt{\frac{L}{\pi\sigma T^4}} = 5\times10^{12} m = 34AU$$

D) Use the Eddington limit equation:

$$m > \frac{L\sigma_T}{4\pi G m_p c} = 6.1\times10^{35} kg$$

E) This is too massive and compact to be anything other than a black hole – presumably with an accretion disk around it.

Question 6

Supernovae – standard candle when calibrated. Use inverse square law to get distances, measure redshifts, plot one versus the other to get $a(t)$ as a function of t. It's accelerating as slope is getting steeper.

Also – BAOs give a standard ruler at a bunch of distances. And old objects at high redshifts. Tied in with flat universe constraint.

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PRACTICE EXAMINATION

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ASTR1001_Semester 1 Astrophysics

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Question 1

Imagine that a new planet has just been discovered, ten astronomical units (AU) from the Earth. The planet appears to have a diameter of one arcsecond in telescope images. A flux of 1.6×10^{-10} W m^{-2} is detected coming from the planet.

A) What is the actual physical diameter of the planet (in km)? **(10 marks)**
B) What is the luminosity of the planet? **(10 marks)**

Question 2

A) Describe what is meant by the reionisation of the universe. **(4 marks)**
B) What observation evidence do we have for when this took place? **(8 marks)**
C) What are the possible causes for the reionisation? **(8 marks)**

Question 3

Imagine that you have been monitoring the apparent brightness of a sun-like star (a star with the same radius, mass and luminosity as our Sun). The observed brightness shows regular dips, due to transits of a planet which is orbiting the star.

The dips occur every 8.0 days. During each dip, the apparent flux from the star decreases by 0.6%.

A) Deduce as much as you can about the planet and its orbit. **(10 marks)**
B) By balancing the incoming and outgoing radiation, estimate the temperature of the planet **(10 marks)**

Question 4

Gravitational microlensing is a new technique for finding exoplanets.

A) How can you find planets by microlensing? What observations must you make? What would you see? **(10 marks)**
B) What are the advantages of the microlensing technique compared to other planet-finding techniques? **(10 marks)**

Question 5

Explain in words (no equations) what a white dwarf star is, and how it can withstand the immense pressure due to its large mass and small radius. **(20 marks)**

Question 6

Imagine that you have discovered a distant galaxy. You take a spectrum of the galaxy, which shows strong absorption lines at the following wavelengths: 441.28nm, 445.21nm, 482.5nm, 517.5nm, 545.4nm, 580.63nm, 660.86nm and 736.37nm.

The galaxy has an apparent radius of 2 arcseconds, and a flux of 1.2×10^{-15} W m^{-2}. You may assume that Hubble's constant is 71 km/s/Mpc.

Deduce as much as you can about this galaxy.

(20 marks)

END OF EXAMINATION

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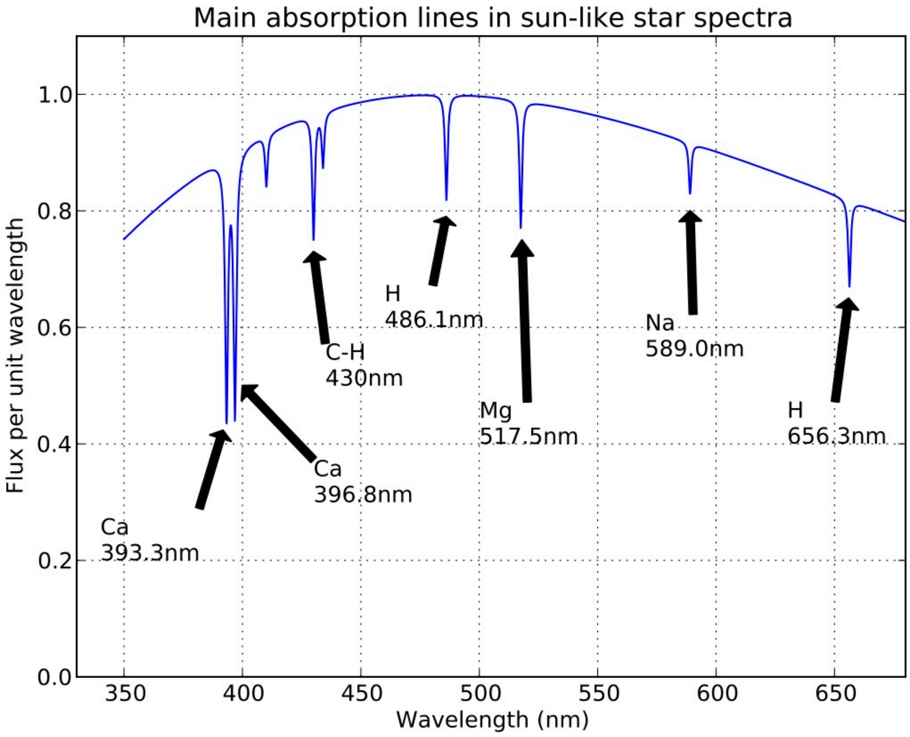

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EXAMINATION

Semester 2 - End of Semester, 2017

ASTR1001_Semester 2 Astrophysics

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Instructions To Students:

Complete all six questions.

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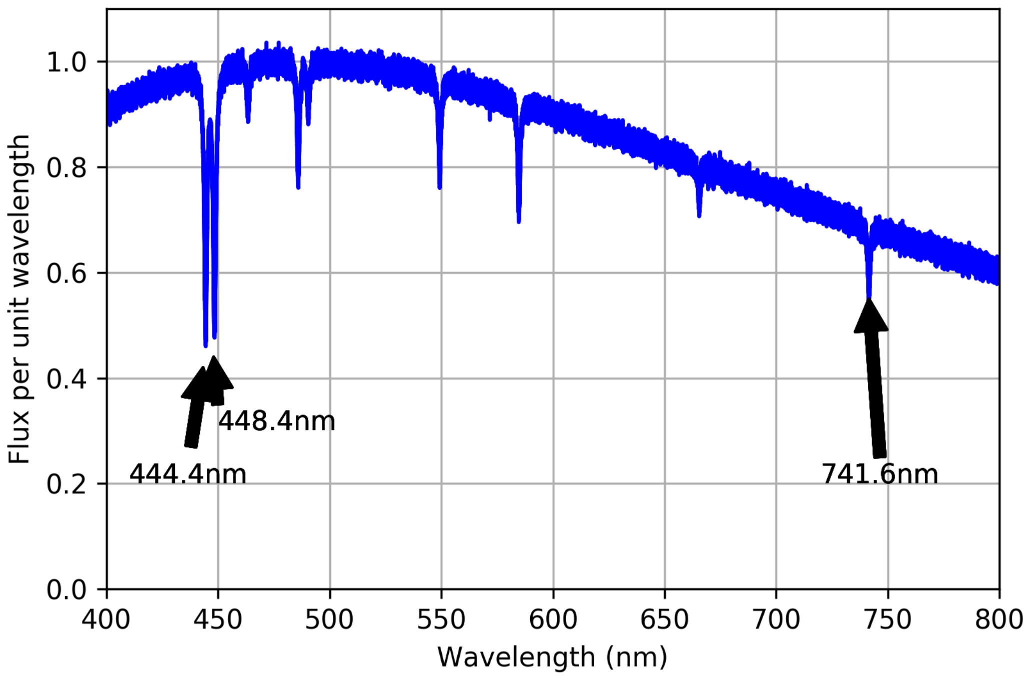
Question 1

Imagine that you have just discovered a distant galaxy. You take an image, and the galaxy shows an apparent diameter of 3.3 arcseconds, and has a flux of 1.4×10^{-15} W m^{-2}.

You also get a spectrum, shown below.



a) What is the redshift of the galaxy? **(4 marks)**
b) What elements are present in this galaxy, based on the above spectrum? **(4 marks)**
c) How far away is this galaxy (you may assume that Hubble's constant is 71 km s^{-1} Mpc^{-1}) in Mega-parsecs? **(4 marks)**
d) What is the true (physical) radius of this galaxy, in kilo-parsecs? **(4 marks)**
e) What is the luminosity of this galaxy (in solar luminosities) **(4 marks)**

Question 2

An exoplanet is in a nearly edge-on orbit around its host star:

The planet is very hot: the side facing the host star (the day side) is hotter than the side facing away (the night side) but both are very hot.

Imagine that the apparent brightness of the star-planet system is being measured with very high precision, at both infra-red and optical wavelengths.

a) Sketch the expected light curve you would observe at optical wavelengths. The light curve should cover one complete orbit. Label the diagram showing where the planet is behind and in-front of the star. **(5 marks)**

b) Mark on the diagram the brightness level of the star alone, and the flux from the planet alone. **(2 marks)**

c) What features of this curve would you use to measure the size of the planet and the reflectivity of its surface? **(3 marks)**

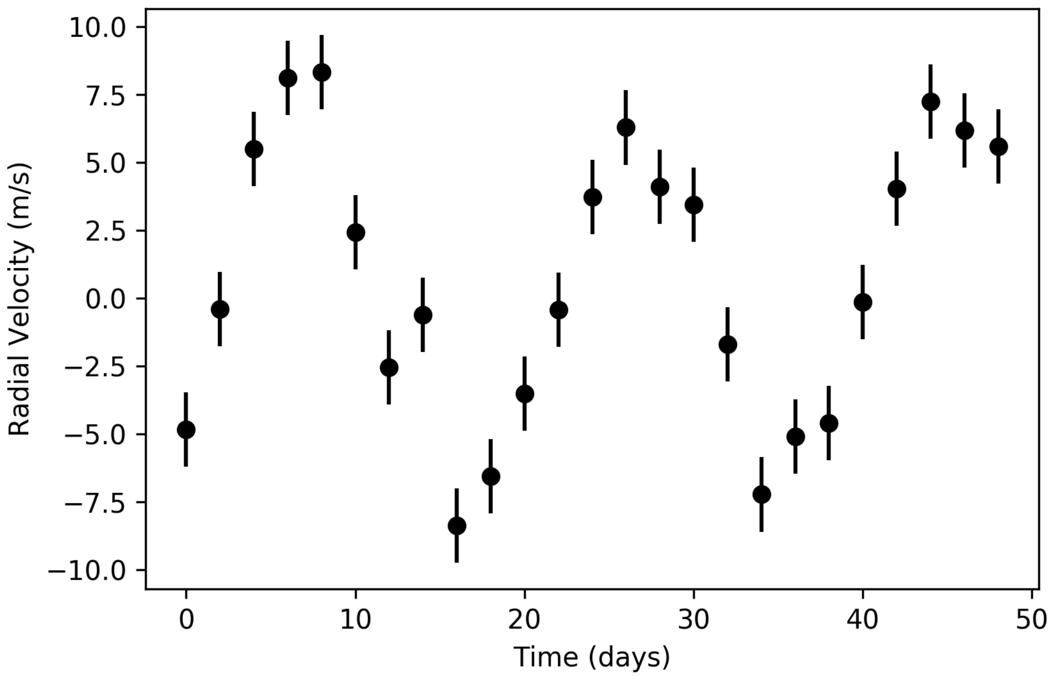
d) Sketch the expected light curve you would observe at infra-red wavelengths. The light curve should cover one complete orbit. Label the diagram showing where the planet is behind and in front of the star. **(5 marks)**

e) Describe how this light curve is different from the optical one, and explain the reasons for these differences. **(3 marks)**

f) Mark on the diagram the brightness level of the star alone, and the flux from the day side of the planet, and the flux from the night side. **(2 marks)**

Question 3

Imagine that you have been observing a nearby dwarf star (mass of 0.32 solar masses, radius of 0.6 solar radii). You have been measuring the radial velocity of this star every second night, using precise doppler spectroscopy, with a velocity uncertainty of 1.37 m/s. Here are the data you obtained:



Note that positivity radial velocities indicate motion of the star away from you. The radial velocity oscillation suggests that a planet is orbiting this star.

A) Based only on these radial velocity data, what can you deduce about the orbital radius and mass of this planet? Explain your reasoning. **(10 marks)**

B) You decide to try to see if there are transits in this system. It turns out that another astronomer had been observing the brightness of this star over the same 50 days that you observed. On roughly which days might you expect to have seen transits, if any were present? Explain your reasoning. **(4 marks)**

C) Imagine that you did indeed see transits at these times, and during transit, the brightness of the star decreased by 1.2%. What new facts can you deduce from this extra information? **(6 marks)**

Question 4

A thermo-nuclear supernova has just exploded. Before the explosion, it was a white dwarf of mass 3.0×10^{30} kg, made entirely of carbon (C_{12}). During the explosion, the carbon was completely transformed to iron (Fe_{56}). C_{12} has an atomic mass of 12.0 u, and Fe_{56} has an atomic mass of 55.9349375 u.

A) How much energy is released by the explosion? **(8 marks)**
B) If all the nuclear energy is released as radiation, and the supernova radiates with a uniform brightness for ten days, what is the luminosity of the supernova? **(4 marks)**
C) If the supernova is 93 Mega-parsecs from the Earth, what fluence will be observed on Earth? **(4 marks)**
D) What flux would be observed on Earth? **(4 marks)**

Question 5

A) Describe in words and diagrams (but not equations) why astronomers believe that dark matter exists. **(12 marks)**
B) Two possible candidates for dark matter are:
   a. Vast numbers of free-floating planets or black holes
   b. Some strange non-baryonic sub-atomic particle that does not interact with matter much.

   Discuss the evidence for and against these two candidates for dark matter. Which of them could account for most of the dark matter in our universe? **(8 marks)**

Question 6

Describe and explain the theory of cosmic inflation. Include in your description the puzzles that cosmic inflation claims to explain. **(20 marks)**

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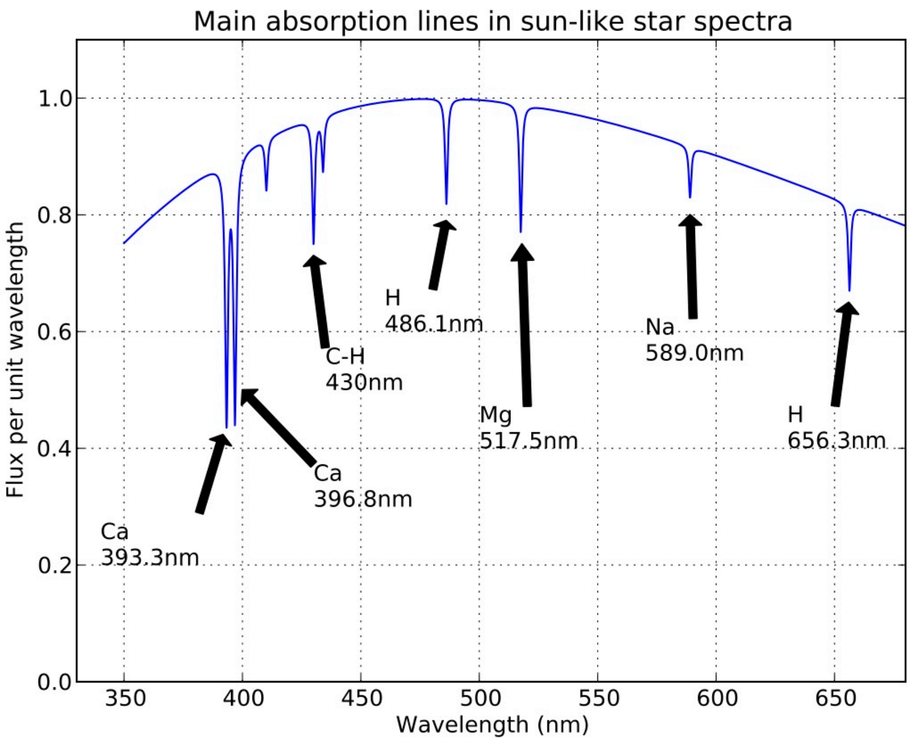

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Inverse Square Law: $f = \frac{L}{4\pi D^2}$

Small-angle approximation: $r = \theta D$ for object of size r, distance D and angle θ radians.

Uncertainty Principle: $\Delta x . \Delta p \geq \frac{h}{4\pi}$

Hubble Law: $v = H_0 D$

Reflex motion or transit: distance to planet: $r = \sqrt[3]{\frac{GM_* P^2}{4\pi^2}}$

Reflex Motion: velocity of star: $v_* = \frac{2\pi r}{P} \frac{M_p}{M_*}$

Eddington Limit: $L_E = \frac{4\pi G M_{\text{star}} m_{\text{proton}} c}{\sigma_T}$

SI Prefixes:

- Giga = 10^9
- Mega = 10^6
- Kilo = 10^3
- Milli = 10^{-3}
- Micro = 10^{-6}
- Nano = 10^{-9}

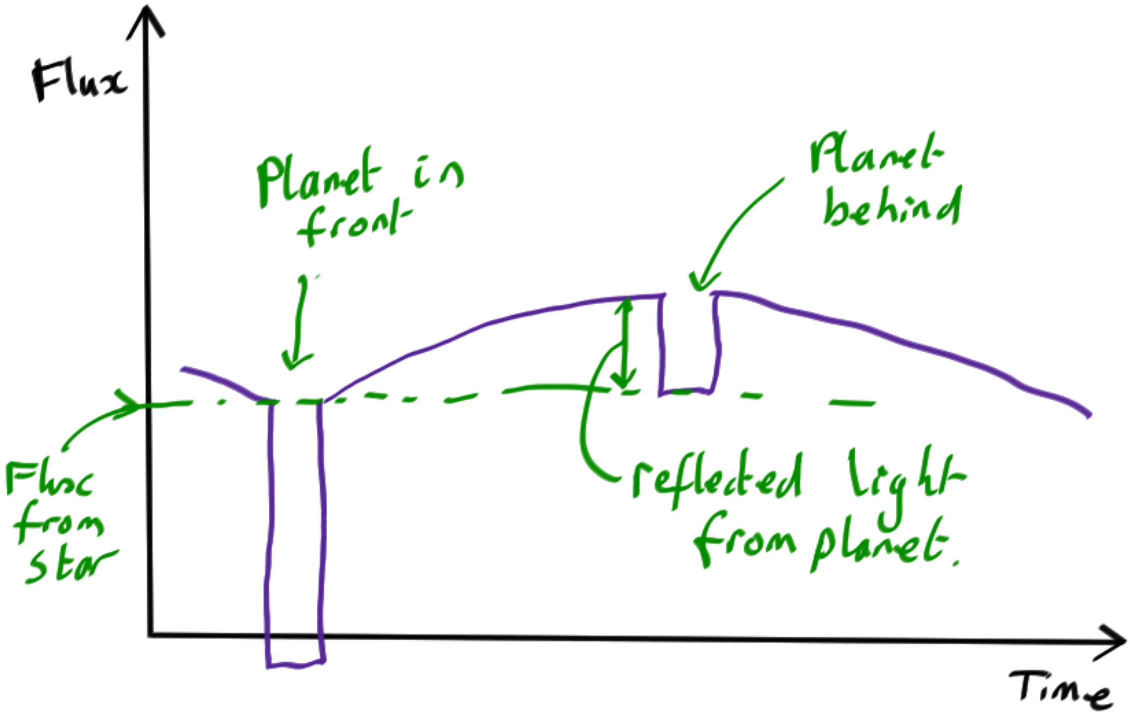
Answers: ASTR Semester 2 Exam 2017

Question 1:

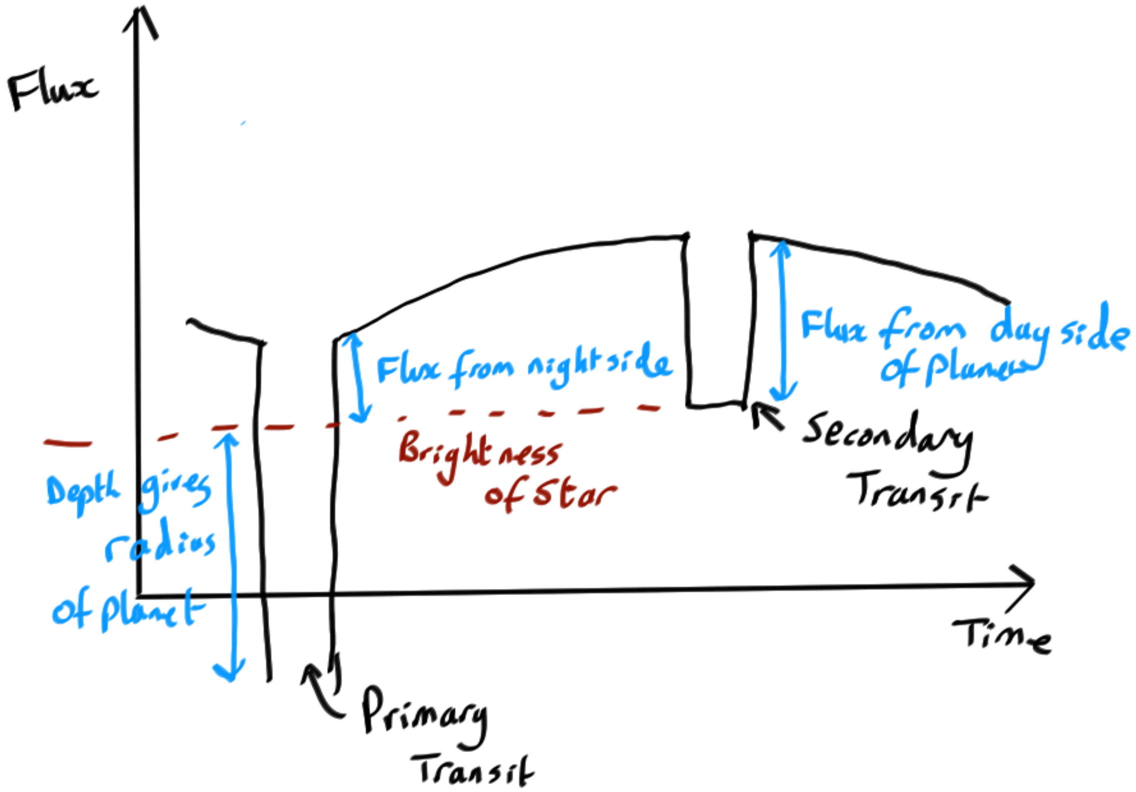
a) Z = 0.13
b) Ca, C, H, Mg, Na
c) 549 Mpc
d) 8.8 kpc
e) 1.32×10^{10} solar luminosities.

Question 2:

a/b)



c) The depth of the primary transit tells you the fraction of the star obscured. If you know the size of the star, this then gives you the size of the planet. The bulge in light gives you the amount of light reflected from the planet, which can be used to calculate the albedo.
d)



Planet is in front at the primary transit and behind as the secondary transit.
e) it is different because the secondary dip goes below the level of the top of the primary transit. This is because there is still emission from the night side of the planet in the IR, but the night side reflects no visible light.

Question 3

A) From the graph, you can measure an amplitude of around 7 m/s and a period of around 20 days (actually 19.5).

The period tells you the orbital radius of the planet, by using
$r = \sqrt[3]{\frac{GM_* P^2}{4\pi^2}}$ to get r = 0.097 AU
Because you don't know the inclination of the orbit, you can't deduce the mass of the planet, only M sin I, which is given by rearranging $V_* = \frac{2\pi r}{P}\frac{M_p \sin(i)}{M_*}$, and comes out as 0.043 Jupiter masses (8.16×10^{25} kg). The real mass will be this big or bigger.

B) The transits will happen when the planet has just finished coming towards us and is moving sideways (i.e. velocity near zero just after a negative spell). These occur at around days 8, 26 and 47.
C) If the dip in brightness is 1.2%, the planet must cover 1.2% of the star disk, so $\left(\frac{r_p}{r_*}\right)^2 = 0.012$. So $r_p = r_*\sqrt{0.012} = 24{,}400\ km$

Question 4

A) Work out mass per nucleon for carbon and Iron. Multiply difference by c^2 then factor in mass of star to get $E=3.1326\times10^{44}$J
B) Divide by number of seconds in ten days to get $L=3.625\times10^{38}$W
C) Energy divided by 4 pi r^2 gives Fluence = 3.027×10^{-6} J m^{-2}
D) Luminosity divided by 4 pi r^2 gives flux = 3.50×10^{-12} W m^{-2}.

Question 5

A Rotation curves, gravitational lensing, x-ray gas, overall cosmology/CMB
B Machos mostly eliminated by microlensing – they exist but are far too few. Subatomic particles – primordial nucleosynthesis says can't be baryons. Not seen in labs.

Australian National University

Venue ____________________

Student Number |__|__|__|__|__|__|__|__|

PRACTICE EXAMINATION

Semester 1 - End of Semester, 2017

ASTR1001_Semester 1 Astrophysics

This paper is for ANU and TU Delft students.

Examination Duration: 180 minutes

Reading Time: 15 minutes

Exam Conditions:

Central Examination

Materials Permitted In The Exam Venue:

One A4 page with notes on both sides. Calculator (programmable is fine). Unannotated paper-based dictionary (no approval required),

(No electronic aids are permitted e.g. laptops, phones)

Materials To Be Supplied To Students:

1 x 20 page plain

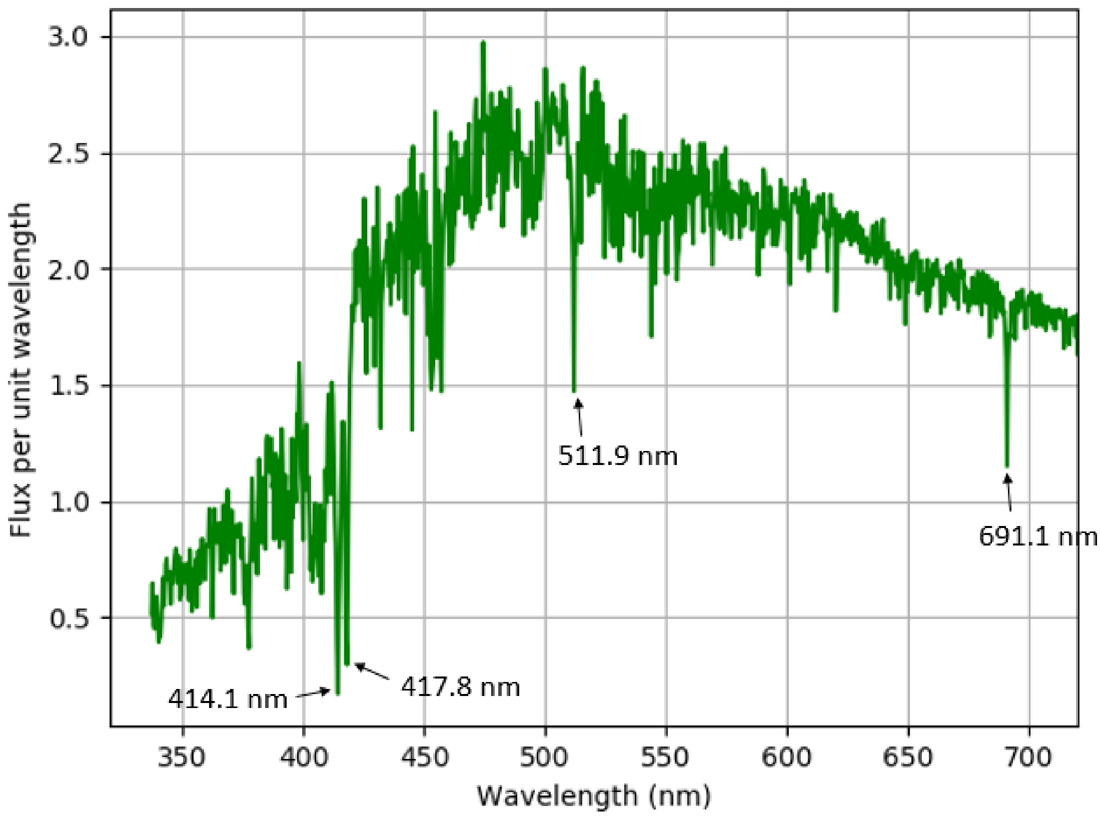
Instructions To Students:

Complete all six questions.

A formula sheet and a list of useful constants and numbers is at the end of the exam paper.

Question 1

Imagine that you have discovered a faint new galaxy. You take a spectrum of this galaxy:



You measure a flux from this galaxy of 8.0×10^{-15} W m^{-2}, and its apparent diameter is 9.1 arcseconds.

Deduce as much as you can about this galaxy. You may assume that Hubble's Constant is 70 km s^{-1} Mpc^{-1}, and that the galaxy has a negligible peculiar motion. Explain your reasoning. **(20 marks)**

Question 2

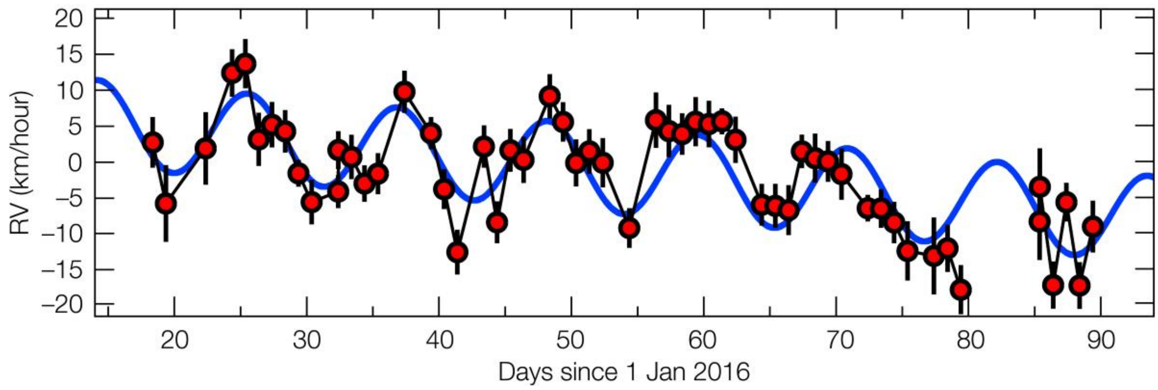
a) What observation could you make to work out whether an observed supernova was a Type 1a or a Type 2 supernova? **(4 marks)**

b) Explain in words how and why these two different types of supernovae explode. **(8 marks)**

c) Both one type of supernova and red giant stars are powered by nuclear fusion. Why do the supernova explode while the stars burn steadily? **(8 marks)**

Question 3

In August 2016 a team of researchers announced that they had detected a planet orbiting the nearest star to our own – Proxima Centauri. The planet was discovered using the radial velocity method: here is the data, together with their best fit (the sine wave).



No transits have been seen in the light curve of Proxima Centauri. Proxima Centauri has only 12% the mass of the Sun.

Deduce as much as you can from these data. Explain your reasoning in words (not just equations). Carefully explain what you can and cannot know about this planet.

(20 marks)

Question 4

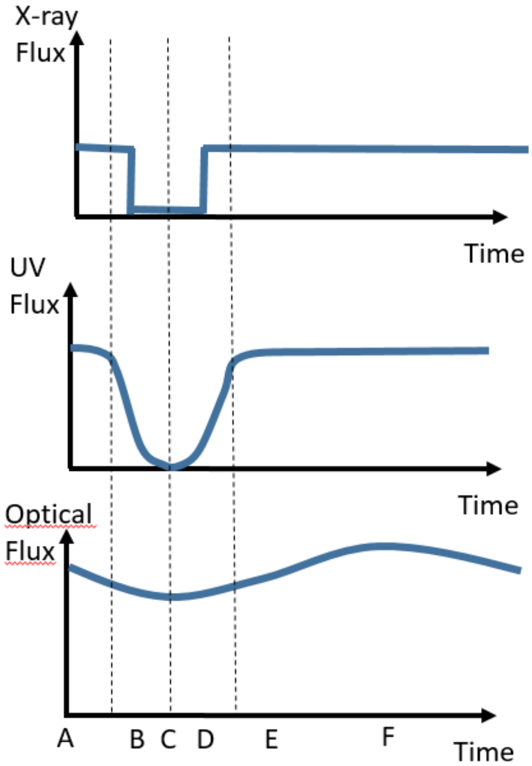
Imagine that you have detected an unknown object, floating all alone in deep space. This object shows a black-body spectrum with a peak at a wavelength of around 100nm, and with a total flux of around $3x10^{-14}$ W m^{-2}. You believe that it is roughly 1000 light years from the Earth.

Deduce as much as you can about this object, clearly explaining your reasoning. **(20 marks)**

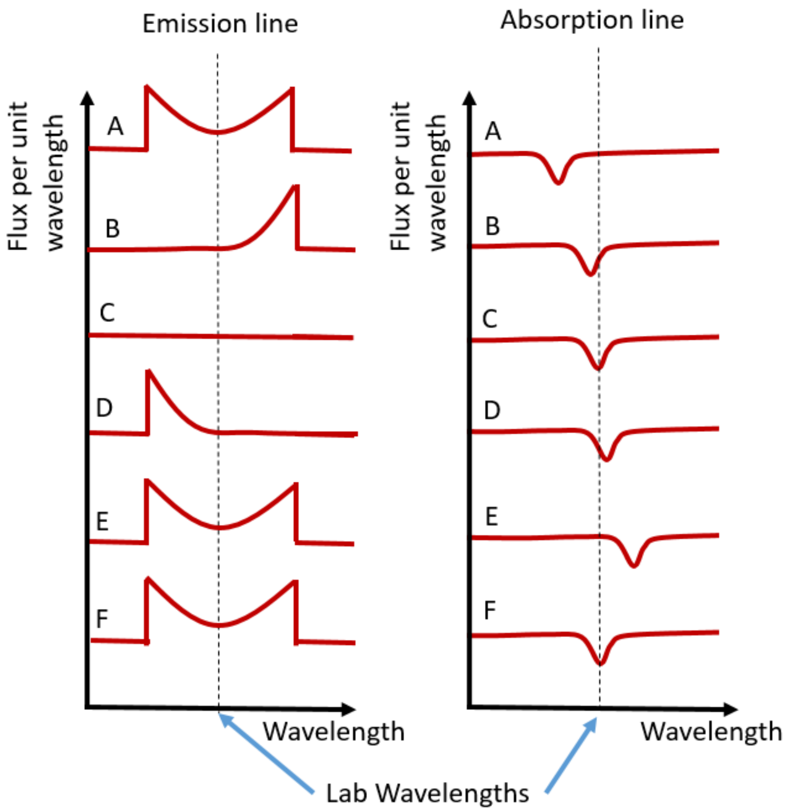
Question 5

Imagine that you have discovered a strange X-ray source out in space. It emits strong X-ray and ultra-violet (UV) light most of the time, though they drop in brightness periodically. Here is the observed light curve. This pattern repeats.

(see the next page for diagrams).



Its optical spectrum looks like the spectrum of a cool red star, with all the normal cool star absorption lines, but in addition, it shows emission lines with a strange double-peaked shape. You obtained spectra at the times A, B, C, D, E and F marked above. Here are zoomed-in views of one typical emission line and one typical absorption line:



You suspect that this object is a binary of some sort.

What can you deduce from these data? Explain your reasoning. Include a sketch of the geometry, labelling the different components of the system, and marking where the times A-F are. **(20 marks)**

Question 6

Explain (using words and diagrams but not equations) what the acoustic peaks in the microwave background are, how they form, and how they can be used to constrain cosmological parameters.

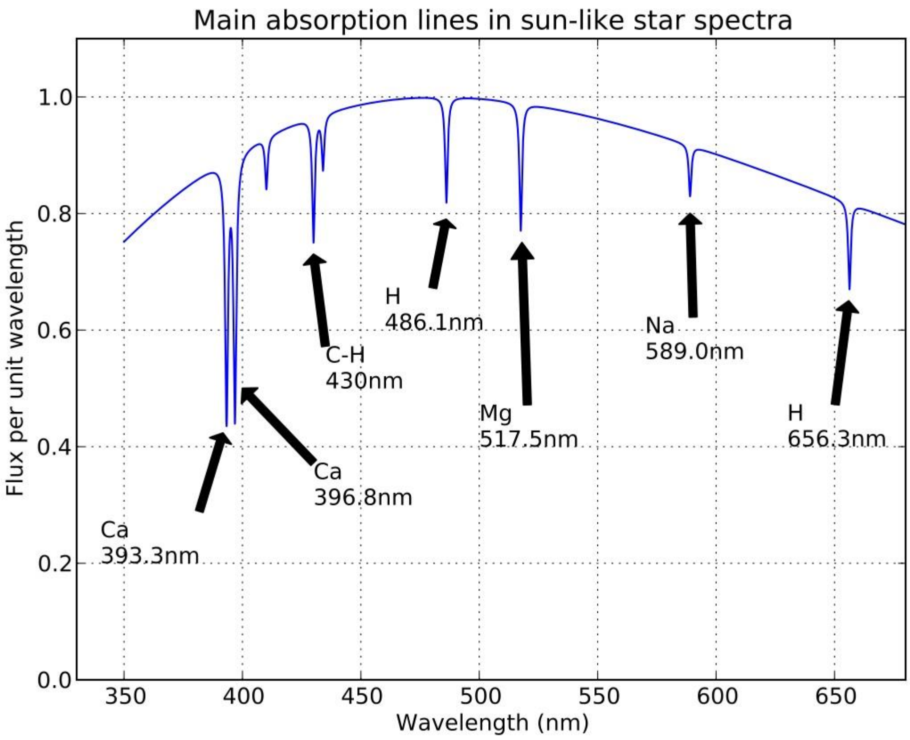
(20 marks)

END OF EXAMINATION

Equations, Physical constants and other data

Speed of light	$c=3\times10^{8}$ m s^{-1}
Universal gravitational constant	6.67×10^{-11} N m^{2} kg^{-2}
Magnitude of charge on electron	$e = 1.6\times10^{-19}$ C
Stefan-Boltzmann constant	$\sigma=5.67\times10^{-8}$ W m^{-2} K^{-4}.
Mass of electron	9.11×10^{-31} kg
Mass of proton	1.67×10^{-27} kg
Planck's constant	$h = 6.636\times10^{-34}$ Js
Volume of a sphere, radius R	$(4/3)\,\pi R^{3}$
Surface area of a sphere, radius R	$4\pi R^{2}$
Radius of Earth	6400 km
Mass of Earth	6×10^{24} kg
Distance of Earth from Sun (AU)	1.5×10^{11}m.
Light year	9.5×10^{15} m
Parsec	3.1×10^{16} m
Solar Mass	2.0×10^{30} kg
Solar Radius	695700 km
Solar luminosity	$3.83\text{x}10^{26}$ W

Thompson cross-section: $\sigma_T = 6.7 \times 10^{-29} m^2$



Newton's Law of Gravity: $F = \frac{GMm}{r^2}$

Doppler Effect: $\frac{v}{c} \approx \frac{\Delta\lambda}{\lambda}$

Redshift: $z = \frac{\lambda - \lambda_0}{\lambda_0}$

Centripetal Force: $F = \frac{mv^2}{r}$

Stefan-Boltzmann Equation: $L = A\sigma T^4$

Wien Displacement Law: $\lambda = \frac{0.0029}{T} m$

Inverse Square Law: $f = \frac{L}{4\pi D^2}$

Uncertainty Principle: $\Delta x . \Delta p \geq \frac{h}{4\pi}$

Hubble Law: $v = H_0 D$

Reflex motion: distance to planet: $r = \sqrt[3]{\frac{GM_* P^2}{4\pi^2}}$

Reflex Motion: velocity of star: $v_* = \frac{2\pi r}{P} \frac{M_p}{M_*}$

Mock Exam Answers:

Question 1:

You can measure the redshift from the spectral lines – the redshift is 0.053 and the labelled lines are the two calcium lines and two hydrogen lines. All match up.

Given this redshift, the Doppler effect equation tells you that the recession velocity is 15,900 km/s. Using Hubble's Constant, this gives a distance of 227 Mpc.

You can then use the inverse square law to work out the luminosity of this galaxy, which comes out as 5×10^{36} W. You can also use the apparent radius to work out the actual radius which is 10 kpc.

Question 2:

From the graph, you can see that the planet is orbiting with a period of around 11 days, and the star is moving at around 6m/s (the amplitude of the blue curve). From the period we can work out how far it is from the star.

Use

$$r = \sqrt[3]{\frac{GM_*P^2}{4\pi^2}} = \sqrt[3]{\frac{6.67\times10^{-11}\times0.12\times2\times10^{30}\times(11\times24\times3600)^2}{4\pi^2}} = 7.15\times10^9 m = 0.048 AU$$

How about the mass?

We know that $v_* = \frac{2\pi r}{P}\frac{M_p}{M_*}$

Rearranging this, $\frac{M_p}{M_*} = \frac{v_* P}{2\pi r} = \frac{6\times(11\times24\times3600)}{2\pi\times7.15\times10^9} = 0.00013$

So the mass of the planet is 0.00013 times the mass of Proxima Centauri – i.e. 3.1×10^{25} kg. (a few times the mass of the Earth). This is a lower limit – it might be more massive if the orbit is not edge on.

Question 3:

a) You should take a spectrum and see if any hydrogen lines are present. If they are present, this is a Type 2 supernova – otherwise it's type 1.
b) A Type Ia supernova is a carbon-oxygen white dwarf star which becomes heavy enough to trigger nuclear fusion, converting the carbon and oxygen ultimately into Iron, and in the process liberating the energy causing the explosion. The reason for the white dwarf gaining enough mass to explode is unclear – maybe a merger or some accretion onto the surface. As the mass increases, the white dwarf shrinks until fusion begins. A Type II supernova, on the other hand, is a massive star that has run out of fuel in its centre, leaving most of the gas unsupported. The gas falls inwards then bounces in the centre. The energy source is the gravitational potential energy liberated as the gas falls in. A vast number of neutrinos are generated in the centre and as they flood out they help drive the explosion.

c) In a star, the nuclear fusion is self-regulating because if the fusion speeds up, the temperature increases, reducing the density, and hence slowing down the fusion. In a white dwarf, on the other hand, the pressure is not supplied by the heat but comes from degeneracy pressure, so as fusion proceeds and raises the temperature, the density does not decrease, so the fusion goes faster and faster, causing an explosion.

Question 4:

From the flux and distance, use the inverse square law to work out the luminosity:

$$L = 4\pi D^2 f = 3.7\times10^{25} W$$

As the spectrum peaks at around 100nm, the temperature can be obtained from the Wien displacement law:

$$T = \frac{0.0029}{\lambda} = 29,000K$$

So it's very hot – a white dwarf or blue supergiant.

Use the Stefan-Boltzmann equation to work out the area and hence the radius of the star, to find out which.

$$L = A\sigma T^4 = 4\pi r^2 \sigma T^4$$

Rearranging, we find that

$$r = \sqrt{\frac{L}{4\pi\sigma T^4}} = 8,600km$$

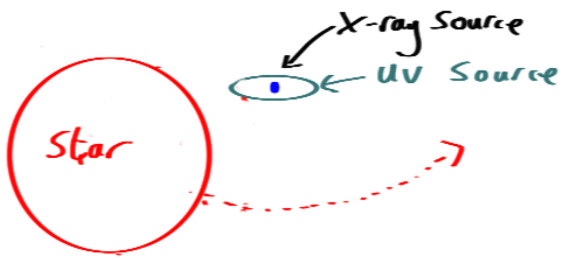
So it's a fairly typical white dwarf star – slightly larger than the Earth.

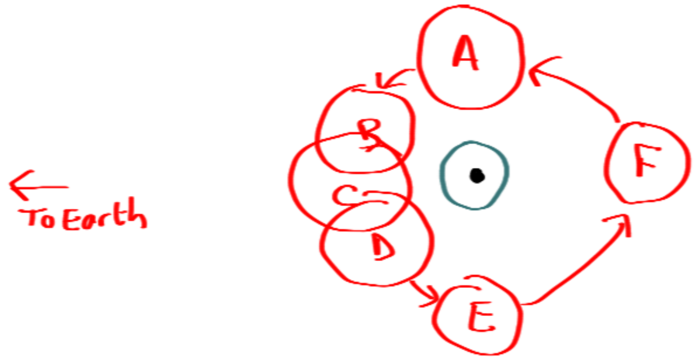
Question 5:

From the light curves, it looks like the UV and X-ray source goes behind the star once per orbit. The X-ray flux dips instantaneously, so it must be a compact source of X-rays. The UV source, on the other hand, dips and recovers in brightness more gently, so it must be a larger, extended source, being partially covered and uncovered.

The optical emission is the starlight (from the spectrum) – and is brightest opposite the X-ray source – presumably the source is heating up or illuminating one side of the star – the side facing it.

From the absorption-line spectrum, the star is moving back and forth – moving perpendicular to the line of sight at C and F (front and back respectively):





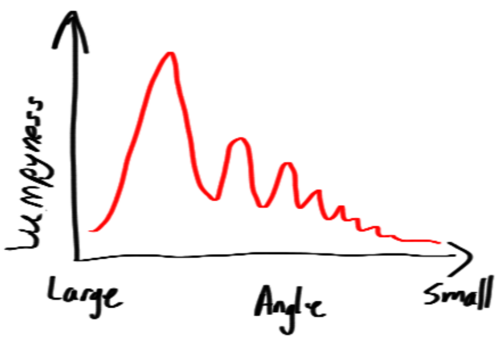
As the star moves across our line of sight, it first blocks one side of the UV source then the other. We see that one side then the other of the emission-line disappears – so it must be a rotating cloud of gas coincident with the UV source, and spinning in the same direction as the star.

The width of the emission line is great, so the gas is spinning fast. But the wavelengths of the peaks do not change, so the whole disk is not moving much – unlike the star, who's velocity shifts substantially.

So – we have something that is much more massive than the star, which is stationary and surrounded by an accretion disk. The much lighter red star is orbiting around this massive x-ray source.

Question 6

The microwave background is not uniform – it has lumps in its observed intensity. You can plot how strong these lumps are as a function of angular size on the sky, and you get a plot like this:



In the early universe, dark matter can move freely but baryonic (normal) matter is very elastic due to the vast numbers of photons trapped within it – the baryon-photon fluid.

At the era of recombination, the baryons become electrically neutral and space therefore becomes transparent, so the photons and matter become uncoupled – the photons going to be the microwave background, and the baryons forming stars and galaxies.

Dark matter forms into lumps of all different scales. The baryon-photon fluid falls into these lumps. On really big scales there isn't time to fall in. The first peak corresponds to lumps of just the right size to have just collapsed before recombination. In slightly smaller lumps, the baryon-photon fluid had collapsed in and rebounded back to average density – this is the first trough. Then you get lumps with the right size for the baryon-photon fluid to have fully rebounded – the second peak, fallen in a again (third peak) etc.

The physical size of the first peak depends on fundamental physics, but its apparent size depends on the curvature of space-time – so it's observed angle measures how curves space is. The ratio of odd- and even-numbered peaks tells us the matter density compared to dark matter – because the odd-numbered ones have matter moving in (its gravity assisting compression) while the even numbered ones have matter moving out.