UNIVERSITY OF EXETER

PHYSICS

JANUARY 20XX

OBSERVING THE UNIVERSE

Duration: TWO HOURS

Answer ALL four questions.

Full marks (100) are attained with four complete answers. (Marks may be subject to scaling by the APAC.)

Use a single answer book for all questions (1 book).

Materials to be supplied:

Physical Constants sheet

Approved calculators are permitted.

This is a ‘closed note’ examination.

1. (i) Assuming a star can be considered to be a blackbody, give an expression showing how its luminosity, L, is related to its radius, R, and temperature, T. **[3]**

It is known that the luminosity and radius of stars on the Main Sequence are linked to their mass, M, via the following relations: $L \propto M^{3.5}$ and $R \propto M^{0.8}$.

Using logarithms, combine these three relations to show that $L \propto T^{7.4}$ for stars on the Main Sequence. Use this to show that stars covering a relatively narrow range in temperature from 2 000–50 000 K span a factor of $\sim 2 \times 10^{10}$ in luminosity. **[8]**

(ii) An astronomer observes a sample of stars and deduces that two of them (Star A and Star B) are Main Sequence stars with identical temperatures of 5 000 K. Briefly outline how the astronomer may have measured these temperatures. **[3]**

However, while Star A is found to have a V-band magnitude of 15.0, Star B has a magnitude of 17.5. Show that Star B must lie ~ 3.2 times further away than Star A. **[4]**

Star B is thought to have a massive exoplanet in orbit around it and the astronomer decides to carry out a photometric monitoring study in search for evidence of a dip in the light curve due to the planet transiting the star. The possible transit is predicted to result in a 1% dip in the stellar flux. To spot such a dip with a signal-to-noise of 10 then requires that the star be detected with a signal-to-noise of 1000, which in turn requires that at least 10^6 photo-electrons be detected. Finally, this must be achieved in a 1 minute integration time in order to track any transit event.

Assuming that a $V = 0.0$ mag star has a flux of $3.5 \times 10^{-9}\,\mathrm{W\,m^{-2}}$ through a V-band filter centred at 5500 Å and a total telescope + detector efficiency of 30%, calculate the minimum diameter of telescope required for the experiment. **[7]**

Turn Over

2. (i) Explain why a molecular cloud collapsing under gravity heats up. Unless this heat is removed, the pressure will increase to a point where collapse is no longer possible and a star will not form. Explain how heat is removed during the early phases of star formation. Explain why this no longer works when the cloud is very dense. **[1, 1, 1]**

Molecular clouds tend to rotate slowly due to interactions with other clouds and other physical processes occurring in a galaxy. Take a rigidly rotating, 0.1 pc radius, $1M_\odot$ cloud with constant density, rotating at $0.1\,\mathrm{km\,s^{-1}}$ at its outer edge. Then assume it collapses down to a Sun-like star, again with constant density, without losing any mass. By considering conservation of angular momentum, calculate the rotational velocity v at the surface of the star after the collapse is complete. **[7]**

Then, by considering centripetal acceleration, show that the gravity of the star is insufficient to hold such a star together. **[3]**

Since stars do actually exist, angular momentum must be removed from the collapsing material as it makes its way to the star. Name three ways in which angular momentum can be removed in the star formation process. **[4]**

[1 pc = 3.1×10^{13} km; radius of the Sun = 7.0×10^{5} km; mass of Sun ($M_\odot$) = 2.0×10^{30} kg]

(ii) Once the formation of a star is complete, there may be some remnant dust in orbit around the star and in thermal equilibrium with it, similar to the zodiacal dust cloud around the Sun.

Using what you know about the Earth, estimate the temperature of dust grains at radii of 0.1, 1, 10, and 100 AU from a solar-type Main Sequence star, and give an approximate value for the peak wavelength of emission at each radius. You can assume the dust acts as a blackbody. **[8]**

Turn Over

3. (i) Solve the following Doppler shift problems.

(a) Calculate the observed wavelength of a line emitted by oxygen at $\lambda = 500.7\,\mathrm{nm}$ by a star moving towards us at $100\,\mathrm{km\,s^{-1}}$. **[3]**

(b) Calculate the observed wavelength of a line emitted by calcium at $\lambda = 396.8\,\mathrm{nm}$ by a galaxy receding at $60\,000\,\mathrm{km\,s^{-1}}$. **[3]**

(c) Calculate the observed frequency of a line emitted by neutral hydrogen at a frequency $\nu = 1420.4\,\mathrm{MHz}$ from a cloud moving away from us at $200\,\mathrm{km\,s^{-1}}$. **[3]**

(d) Calculate the maximum variation ($\pm\Delta\lambda$) in the observed wavelength of the hydrogen Hα line emitted at $\lambda = 653.6\,\mathrm{nm}$ from a star, due to the motion of the Earth around the Sun. **[5]**

[Radius of Earth's orbit = 1 AU = 1.5×10^{11} m]

(ii) Stellar evolution models predict that a star will remain on the Main Sequence until roughly 15% of the available hydrogen has been converted to helium. Stars similar to the Sun have a composition by mass of 73% hydrogen, 25% helium, and 2% heavier elements.

Given that the energy released in the fusion reaction $4\,\mathrm{H} \longrightarrow \mathrm{He}$ (ignoring that carried away by neutrinos) is $\epsilon = 26\,\mathrm{MeV}$, calculate the number of these reactions per second required to sustain the current luminosity of the Sun. **[2]**

How long does it take to convert 15% of the hydrogen to helium? Compare this to the current age of the Sun. **[4, 1]**

Briefly outline the evolutionary stages that a Sun-like star will undergo after leaving the Main Sequence. **[4]**

[Luminosity of Sun ($L_\odot$) = 3.83×10^{26} W; mass of Sun ($M_\odot$) = 2×10^{30} kg; mass of H atom = 1.67×10^{-27} kg]

Turn Over

4. (i) Outline Hubble's morphological galaxy classification scheme, using a labelled diagram. Describe the key physical differences between the two main groupings of galaxies. Which galaxies are missing from the scheme? **[4, 5, 1]**

(ii) A crucial step on the distance ladder to nearby external galaxies are the Cepheid variables, pulsating stars with a magnitude-period relation of the form $M_V = (a \log P) + b$, where M_V is the absolute V-band magnitude, P is the period in days, and the constants a and b are -2.81 and -1.43, respectively.

The Hubble Space Telescope has been used to identify and observe Cepheid variables in nearby spiral galaxies in order to determine their distances. The following table shows the resulting period in days and *apparent* V-band magnitude, m_V, for Cepheids identified in M 100, a face-on spiral galaxy in the Virgo cluster:

Cepheid number	Period (days)	m_V
10	50.0	24.81
23	39.7	25.69
48	24.7	25.92
60	17.1	26.15

Use the Cepheid relation to calculate the mean distance modulus and the mean distance in megaparsecs to M 100, taking the Galactic foreground extinction ($A_V = 0.41$ mag) towards M 100 into account. **[7]**

Briefly describe the techniques used to determine distances on the following scales:

(a) within a few hundred parsecs of the Sun; **[3]**

(b) from nearby galaxies out to redshift $z \sim 2$; **[3]**

(c) from galaxies outside the Local Group to the edge of the visible Universe. **[2]**

END OF PAPER