Question 18 **(16 marks)**

What matters in the universe?

In the early 1930s Fritz Zwicky observed a cluster of galaxies in the constellation of Coma. Zwicky found that these galaxies were moving much too quickly for them to be held together in a cluster, by gravity, if the only mass in the cluster was that of the galaxies themselves. This meant that the centripetal force required was greater than the gravitational force available.

Zwicky could not find any evidence of extra mass in the Coma cluster, from the visible light detected by the telescopes he used. He thought that there must be a lot of extra matter that is also present in the cluster, but this matter did not emit visible light and was therefore 'dark'.

In the early 1970s, diffuse X-ray emission from the Coma cluster of galaxies was observed. These diffuse X-rays indicated the presence of a lot of mass that was different to the matter already observed from the visible light of the galaxies. This matter was in the form of plasma and did not emit visible light, but it did emit X-rays as it was very hot. This observation was further evidence that Zwicky had been correct in his ideas forty years previously.

Also in the 1970s, Kent Ford and Vera Rubin analysed the rotational velocity of several galaxies. Astronomers knew that Hubble's law meant that galaxies were moving further apart and were rotating due to the Doppler shift. Hubble's cosmological red shift provided evidence of an increasing distance between galaxies, while the Doppler shift explained why rotating galaxies appeared blue-shifted on one edge while the light from the other edge appeared red-shifted.

A more detailed observation of the stars at the edge of the galaxy revealed that the stars were travelling at a high velocity, but did not leave the rotating system as earlier thought.

Ford and Rubin concluded that for the stars on the edge of the galaxy to be bound together and be part of the rotating galaxy, more mass was required. This mass had to be greater than could be accounted for from the mass of the stars, plasma, gas and dust of the known galaxy. This provided further evidence for the existence of matter that was 'dark'.

It is now theorised that 80% of all matter in the universe is dark matter. This theory considers two types of dark matter; 'hot, non-baryonic dark matter' and 'cold, non-baryonic dark matter'. Hot, non-baryonic dark matter, like fast-moving neutrinos, has mass and reacts with other matter only via gravity (and the weak force). For now, cold, non-baryonic dark matter is also hypothesised to exist.

(a) Use mathematical reasoning to explain why scientists might have believed that the stars at the outer edges would leave the rotating galaxy. (5 marks)

(b) What hypothesis was made to account for the observation that stars on the outer edge did not leave the rotating galaxy? (2 marks)

(c) Describe how red shift and blue shift are produced and how this informs astronomers on Earth that galaxies are rotating. (5 marks)

(d) Discuss how Hubble's Law supports the Big Bang theory. (4 marks)