**Activity 1 – Evidence for Dark Matter**

**Research Questions**

1. Making accurate measurements of the motions of objects in far off galaxies is not a simple matter. How did astronomers such as Vera Rubin conclude that stars were actually orbiting around the center of the galaxy? How accurate were the observations?

Astronomers use a technique called doppler shift to measure the velocity of stars. Absorption lines in the spectrum of light from stars are blue shifted as stars moved towards us and red shifted as they move away from us. By looking at the doppler shift of stars as they orbit around the galaxy astronomers can determine how fast stars are moving. Additionally, astronomers are also able to use radio emissions from Hydrogen gas clouds when they can’t see stars. Hydrogen emits microwave radiation with a 21 cm wavelength when electrons in the ground state flip their spin state. Astronomers can measure a doppler shift in the wavelength of this emission line and determine the orbital motion of gas clouds.   
  
Measuring doppler shifts with precise equipment can be extremely accurate, yielding velocity to within a few tens of m/s.

1. Initially, the existence of dark matter was not the only hypothesis proposed to explain the anomalous motions of galaxies and clusters. Carl Sagan once said, “extraordinary claims require extraordinary evidence”. Accumulating that evidence would take decades. In addition to the existence of dark matter, what other possible explanations for the anomalous motion of galaxies have been proposed?

Several different explanations have been proposed over the decades.

Modified Newtonian Dynamics – This theory of gravity would see gravity act differently on galactic and extra-galactic scales than it does on solar system sized or smaller scales. It would preserve all the features of Newtonian Gravity in situations where it has been tested and demonstrated to work but change how it influences masses on larger scales.

Black holes, rogue planets, and failed stars – If there are enough of these dark objects, they may provide the necessary mass in the galactic halo. They are sometimes referred to as a different category of dark matter known as Massive Compact Halo Objects (MACHOs) but are distinct from other dark matter candidates because they are made from well understood protons, neutrons, and electrons.

**Nature of Science Questions:**

1. Why did it take several decades for enough evidence to be found to conclusively demonstrate the existence of dark matter?

At first the observations were too crude to be conclusively accepted. As more evidence accumulated and instruments improved, the uncertainties of the measurements decreased and it was difficult to dismiss the findings. Once the anomalous motion of stars and gas clouds was firmly accepted there were several different explanations that were proposed. Each of these explanations would lead to different consequences in terms of the motion of stars, the percentage and type of elements in the universe and required energy to produce different particles. As new detection methods were developed different theories were ruled out or supported. It is only with the accumulation of observational evidence and the development of a theoretical understanding was the existence of dark matter generally accepted by the physics community.

1. What were some of the important tools required to make the necessary observations in support of dark matter?

Telescopes, Spectroscopes, Radio Telescopes.

1. Both theoretical and empirical (observational) evidence is important in developing our understanding of dark matter. Explain how each has been used to support the presence of Dark Matter in the universe.

Empirical evidence comes in the form of observations; these have primarily been the rotation rates of stars and gas clouds in galaxies. Other important observations include interacting galaxies like the Bullet Cluster; this cluster consists of two main galaxies that are colliding. As the galaxies collide, the visible matter and gas are slowed gravitationally and can be measured spectroscopically. Because mass warps space, the mass of the galaxies causes gravitational lensing. By looking at the light from galaxies behind the pair of galaxies and how that light is bent as it passes through the cluster it is possible to deduced where the mass of the galaxy is located. Using the observations of gravitational lensing indicates that most of the the galaxies’ mass does not coincide with the visible matter.

Theoretical understanding of dark matter allows physicists to predict and explain the properties of dark matter. By using the laws of physics (conservation of energy, conservation of momentum, conservation of charge, virial theorem, . . .) physicists can construct models of dark matter and predict how it should interact. These predictions can be tested against further astronomical observations or those done in experiments designed to directly detect dark matter.

Theoretical and empirical evidence compliment each other and provide scientists with powerful ways of examining the universe.