FYI

The Cosmological Distance Ladder

How do we measure the distance to the outer reaches of the universe if we can never go there?

Figure 2-2: Image of the Gravitational Lens in Galaxy Cluster Abell 1689

Astronomers use a variety of techniques to measure distance. The distance between Earth and the sun has been measured quite accurately by reflecting radar pulses off the sun and terrestrial planets. Therefore, the Earth-sun distance (1 AU) is a well-defined basis for all other distance measurements. Measurements to stars outside, but relatively close to, our solar system can be estimated with **parallax**, which relies on the Earth-sun distance measurement. With parallax measurements, the distance to more remote stars can be inferred using various techniques of comparing the relative brightnesses of stars. Eventually, supernovae in distant galaxies are compared to closer supernovae to infer the distances to the outermost observed objects in the universe. However, each step of this **distance ladder** depends on the accuracy of the rung below it.

We can use the parallax method to measure the distances to nearby stars by observing their motion against the background sky. As Earth orbits the sun, the relative position changes between foreground stars (those that are closer to us) and background stars (those that are farther away). The closer the foreground star, the greater the apparent shift. By using the known distance between Earth and the sun, we can calculate the distance to a foreground star based on the amount of shift we detect. For stars that are too far away, the shift is too small to detect, so we can only use the parallax method for nearby stars, those up to about 150 light-years away—this includes some relatively nearby star clusters. Parallax is an accurate measurement technique for nearby stars, but becomes less and less accurate as we move farther from Earth due to the increasing difficulty of accurately measuring small angles.

To measure distances to star clusters that are greater than 150 light-years away, astronomers compare the brightness of stars in those clusters to stars in a nearer cluster for which they are able to calculate a distance using parallax. When many stars from the same cluster are plotted on a Hertzsprung-Russell diagram, a graph of brightness vs. temperature of stars (see *Investigating Stars* for more information), most stars lie on the main sequence—a roughly straight line running from the upper left (bright and hot) region to the lower right (cool and faint) region of the diagram. The shape of the graph is generally the same for most clusters, but the overall brightness of the cluster will vary depending on the distance of the cluster. Clusters that are closer will appear brighter overall, and clusters that are farther away will appear dimmer. By measuring how much the brightness of the main sequence of a distant cluster has to be shifted in order to match the brightness of a known cluster closer to us, astronomers can determine the distance to the far cluster. This method, called **main-sequence fitting**, can be used for clusters throughout our own galaxy because normal main sequence stars are at close enough distances to be resolved. Some of those clusters also contain pulsating stars called **Cepheid variable stars**.

If we use the information from main-sequence fitting to determine the brightness of closer Cepheids, we can then find the distance to Cepheids that are farther away, even in galaxies outside our own. In a Cepheid variable star, there is a constant imbalance between the force of gravity pulling toward the center of the star and the thermal pressure outward from nuclear fusion. Therefore, the star expands and contracts periodically, which causes it to get brighter and dimmer. The period of the brightness fluctuation increases as the absolute brightness of the Cepheid increases, so brighter stars take longer to pulse in and out, while dimmer Cepheids have a faster period.

Since the period of brightness fluctuation of a Cepheid variable star is an indicator of its absolute brightness, then by comparing the period of one Cepheid to another we can learn how much brighter one is than the other. If we know the distance to one of them, then we can use this information to get the distance to the other.

Cepheid variable stars have become one of the most reliable distance indicators within our own galaxy and for many nearby galaxies—some of which also contain another distance indicator called a **Type Ia supernova**. A Type Ia supernova is the explosive death of a white dwarf star that has a red giant star as a binary companion. As the red giant expands, its outer layers are gravitationally attracted to the white dwarf, so the white dwarf increases in mass.

The structure of a white dwarf can only support a limited amount of mass before becoming a violent supernova. That mass limit is exactly the same for every white dwarf, which means that the peak brightness of the explosion will be the same for every Type Ia supernova. We can measure the apparent brightness of a Type Ia supernova at its peak and compare that to the known peak brightness of these objects to calculate the supernova's distance.

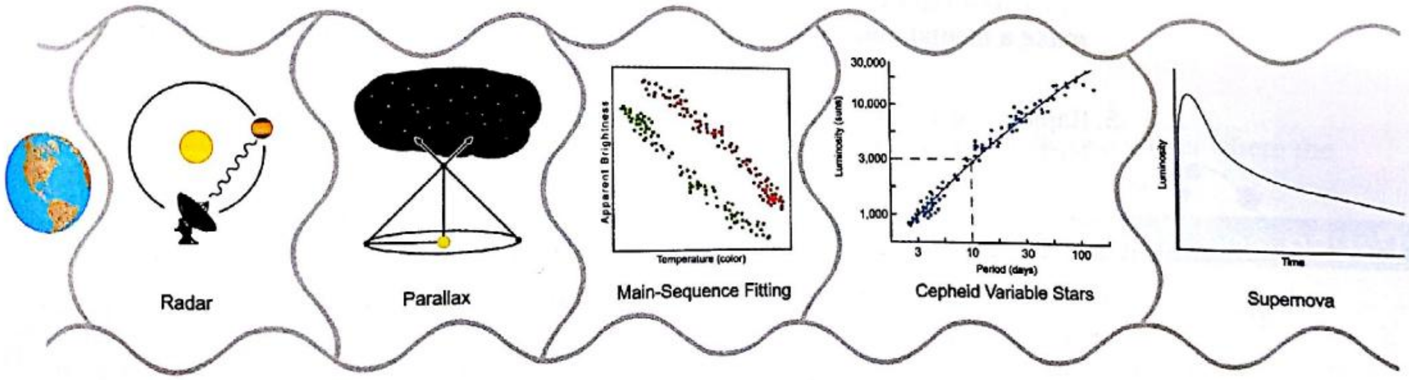

Figure 2-3: Diagram of Distance Ladder: Radar, Parallax, Main-Sequence Fitting, Cepheid Variable Stars, and Type Ia Supernovae

By comparing the brightness of Type Ia supernovae in distant galaxies to those in nearby galaxies, we can determine the relative distance between the closer and distant galaxies.

Together, these techniques enable us to estimate the distances to some of the most distant objects in the observable universe.

Checking In

1. Which technique for measuring distance serves to measure to the most distant galaxies?
2. Why must there be overlap in the distance ladder, such as star clusters that can be measured by parallax and main-sequence fitting, or galaxies that contain both Cepheids and Type Ia supernovae, in order to calculate the distance to faraway objects?