

PHAS 1102

Physics of the Universe

<http://zuserver2.star.ucl.ac.uk/~idh/PHAS1102>

Partial Notes, Part 2, Section 2

Distance Scales – II

These partial notes should be used in conjunction with your own notes, and the powerpoint slides which will be made available on-line.

Refresher

‘Local’ distance scales – appropriate for use within our own Galaxy – have been covered previously in PHAS1102. Recall that the basic unit of astronomical distance is the *parsec*,

$$1\text{pc} = 3.08568025 \times 10^{16}\text{m};$$

an object at a distance of one parsec subtends a *parallactic* angle of one *second* of arc for a baseline of the Earth–Sun distance. The nearest star (other than the Sun) is slightly over one parsec away, so this is a very handy unit for stellar distances. (‘Light years’ are commonly used in the popular press, but never in the scientific literature; 1 pc = 3.26 ly.)

Astronomers measure the brightness of stars on a scale of *magnitudes*. We distinguish between *apparent* magnitudes (the observed brightness), and *absolute* magnitudes (the apparent magnitude an object would have if it were at a distance of 10 pc) – the latter therefore being a measure of a star’s *intrinsic* brightness.

The magnitude scale goes the ‘wrong way’, in that numerically bigger magnitudes correspond to fainter objects; also, it is a logarithmic scale, with a magnitude *difference* of 5m corresponding to a brightness *ratio* of a factor 100. Formally,

$$\Delta m = -2.5 \log \left(\frac{f_1}{f_2} \right).$$

The zero-point of the magnitude scale is arbitrary, based on observations made in antiquity. The brightest stars have apparent magnitudes of about zero (the brightest star, Sirius, has a visual magnitude of -1.5), and the faintest stars comfortably visible from a reasonably dark site are around 5th magnitude, i.e., $100\times$ fainter. Telescopically, objects down to about magnitude 28 or so have been measured.

1 Setting the scene

A variety of techniques can be used for determining distances of individual stars. Where these don't involve intermediate steps, they are known as *primary* distance indicators. Primary distance indicators based on simple geometric techniques (like parallax, the convergent point of moving star clusters, or nova-shell expansion) are generally considered the most reliable, but are generally applicable only to relatively nearby objects, because it's for these objects that angular displacements are largest and easiest to measure.

The best parallaxes, from the *Hipparcos* satellite, give reliable distances out to a few hundred parsecs. However, our Galaxy is of order 10 *thousand* parsecs (i.e., 10 kpc) in radius, and other galaxies are at distances normally measured in Mpc. We need other methods to measure these distances, methods which almost always involve *secondary* distance indicators – methods which rely on other techniques to establish a scale or zero-point (for example, spectroscopic parallaxes require calibration through trigonometric parallaxes). This introduces us to the ‘distance ladder’; distances to nearer objects are found, then these distances are used to calibrate another method which works out to larger distances, and so on, rung by rung, up the ladder. So-called ‘standard candles’, objects, of (supposedly) known intrinsic brightness, constitute important rungs in the distance ladder.

2 Cepheid variables

Cepheid variables (or just ‘cepheids’) form a crucial step in the distance ladder, and are one of the most important standard candles. Cepheids are stars that pulsate in a very regular manner, changing in size, temperature, and brightness with periods of a few to many days (the name comes from the prototype, the star δ Cephei). They are *hottest* when smallest; the greater surface brightness associated with the higher temperature is more important than the smaller surface area, so they are also *brightest* when smallest.

Cepheids play a central role in the historical development of our understanding of the distance scale of the universe, with the first breakthrough being Henrietta Swan Leavitt's identification and measurement of Cepheids in the Magellanic Clouds, a century ago. She found that “there is a simple relation between the brightness of the variables and their periods. . . Since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light”. In modern parlance, Leavitt had shown that there is a *Period–Luminosity (P–L) Relationship* for Cepheids.¹

¹Pulsation properties depend on the abundances of metals; star colours also vary with abundances (though this

This was the first crucial discovery: simply by measuring the pulsation period (relatively easy to do, by taking a series of images), we can, in principle, determine the intrinsic brightness of a Cepheid; knowing the apparent brightness, we then have the distance.

A second key to the central importance of Cepheids is that they are supergiant stars – intrinsically luminous (typically thousands of times brighter than the Sun), and so observable to large distances.²

2.1 Calibrating Cepheid distances

The problem was that, at the time of Leavitt’s work, no-one knew the distance to any Cepheid, so although it was now possible to measure relative distances, it was still not possible to measure absolute distances.

2.1.1 Direct/semi-direct methods

Calibrating Cepheid distances remains troublesome; a handful are at the limits of reliable observability with *Hipparcos*. Others are found in open clusters; the distances to the clusters (and hence the Cepheids) can be found by main-sequence fitting. This gives us distances to a number of Galactic Cepheids, which calibrate the P–L relationship.

2.1.2 Baade-Wesselink

We can measure the change in radial velocity of a Cepheid as it pulsates (i.e., as the surface moves in and out). Because velocity is just dr/dt , integrating the radial-velocity curve gives us the *absolute* change in radius over a pulsation cycle, as noted by Baade (1926) and Wesselink (1946).

We then have two possibilities:

- The change in brightness of a Cepheid over a pulsation period resulted from changes in temperature and in size. By correcting for the temperature variations (which can be measured, e.g., through changes in colour), the analyst can infer the *relative* change in size, just from the change in brightness. Knowing both the absolute and relative *change* in size,

is only a second-order effect – the dominant dependence is on temperature). You may therefore also see reference to a period–luminosity–colour (PLC) relation.

²There are other types of pulsating star which are used in a similar way [e.g., RR Lyrae stars, Mira variables, etc.], but Cepheids alone combine the desirable properties of extreme regularity and intrinsic luminosity.

we can obtain the radius of the star (at any point in the pulsation cycle). If we know the radius and the temperature we can compute the intrinsic luminosity; and if we know the intrinsic luminosity and the apparent brightness we can calculate the distance.

- By using the latest instrumentation (like the VLT interferometer) it is (just) possible to measure directly the angular sizes of a few Cepheids, through a pulsation cycle. If we know both the absolute change in radius, and the change in angular size, we can infer the distance directly, from simple geometry. This ‘geometric Baade-Wesselink method’ is potentially very reliable.

2.1.3 Inverting the problems

A final option is to try to determine the distance to (e.g.) the Large Magellanic Cloud by other means, and then use the adopted distance to calibrate the Cepheid P–L relationship. Techniques include

- Spectroscopic parallaxes
- Eclipsing binaries
- ‘Tip of the red-giant branch’ (or the ‘red clump’)
- Supernova 1987A (by analogy with nova-shell expansion, although we see the expanding ‘flash’, not expanding material)

3 Going beyond...

Once the P–L relationship is calibrated, we can use it to estimate the distances to any galaxy in which we can identify Cepheid variables.

Other indicators include novae, or individual bright ‘normal’ stars.

At still greater distances – beyond the Virgo cluster (~ 17 Mpc) – it becomes impossible to see individual stars, and we have to use other techniques.

3.1 Tully–Fisher

Although one might, as a rough approximation, assume that all spiral galaxies have the same intrinsic luminosity, and thereby estimate distance to remote objects, Tully–Fisher improves on this.

The Tully-Fisher relation is an *empirical* relationship between the rotational velocity of a spiral galaxy, and its total brightness (absolute magnitude): the larger the rotation velocity, the smaller (brighter) the absolute magnitude.

Although this is an empirical relationship, it is easy to see a physical basis: the rotational velocity is a rather direct measure of the total mass of a galaxy, and one might reasonably suppose that more massive galaxies are more luminous (having more stars).

[The corresponding relationship for elliptical galaxies is called the *Faber-Jackson* relation, but here the situation is slightly more complicated by a significant third parameter (surface brightness).]

3.2 Hubble’s Law

Eventually, all methods become unreliable or impractical. However, we can nearly always measure the velocities of distant galaxies, and they are always found to be receding from us. Hubble discovered that there is a simple linear relationship between distance d and velocity v :

$$v = H_0 d.$$

This is *Hubble’s law*. We measure velocities in km s^{-1} and galactic distances in Mpc, so the natural unit of the Hubble Constant, H_0 , is $\text{km s}^{-1} \text{Mpc}^{-1}$. If we know H_0 , we can measure the distance to a galaxy from its redshift, as long as Hubble’s law holds. (Of course, this is a bit chicken-and-egg; we need to know the distances to galaxies to establish the Hubble constant...)

3.3 Type Ia SN

At large distances, Hubble’s law must break down. This will be covered in greater depth when we consider cosmology, but for now it’s enough that we would like a ‘standard candle’ that is observable to very great distances. We now have such a tool: Type Ia supernovae.

Supernovae come in several ‘flavours’; the most common are core-collapse supernovae, which (as the name suggests) arise from the collapse of very massive stars at the end of their lives, when

they run out of nuclear energy sources. Although bright, these don't make good standard candles, because the brightness of the supernova depends on the (unknown) mass of the progenitor.

A second class of supernova arises from the entirely distinct process of accretion onto a white dwarf in a binary system. As the mass approaches the 'Chandrasekhar limit' of $1.4M_{\odot}$, the increasing temperature and density results in ignition of carbon fusion. This proceeds very rapidly, releasing huge amounts of energy in a few seconds.

Because all such 'Type Ia' supernovae originate in much the same way, they all have similar absolute magnitudes. Moreover, they are enormously luminous – often as bright, or brighter, than the entire host Galaxy. They are now the favoured means of measuring objects at large distances (of course, we can only measure them where they occur!), although their absolute magnitudes still have to be calibrated through intermediate means; in particular, only about 10 Type Ia SNe have occurred in galaxies close enough for their distances to be measured with Cepheids.