Pulsating Stars and the Cosmic Distance Scale

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I INTRODUCTION

In this paper we propose to discuss pulsating stars and the part that they have played in the determination of the 'cosmic distance scale'. What do we mean by the 'cosmic distance scale'? Loosely speaking, it may be thought of as the size scale of the observable universe. A little latter we shall explain what we mean by the term 'observable universe'. Thus, the 'radius' of the observable universe ought to be one or two (or a few) times this cosmic distance scale. Further discussion of the cosmic distance scale may be found in Sections III and IV.

In Section II we shall discuss Cepheid variables as pulsating stars, and in Section IV the famous 'period-luminosity relation' of Cepheids. We shall discuss briefly the accepted instability mechanism of Cepheids in Section V. Finally, in Section VI we shall present some recent results primarily regarding the cosmic distance scale and some conclusions.

It is a bit sobering to realize that the distance scale of the universe, and the immense distances of other galaxies, have been known about for only a little more than half a century. Even the enormous distances of the stars have been realized for certain for not quite a century and a half. However, Newton had a suspicion that the stars must be very far away. He even had a rough idea of their distances, some two hundred years before the first stellar distances (of three stars, to be exact) were actually measured independently by Bessel, Henderson, and Struve in 1837.

For orientation, it might be useful to examine our place in the universe, according to current thinking. We live on the earth, practically a sphere about thirteen thousand kilometers in diameter. (A kilometer is a little more than half a mile, more exactly 0.6 miles.) The earth revolves about the nearest star, the sun, at a distance of about one hundred fifty million (thousand thousand) kilometers. The earth is one of nine planets revolving about the sun, and constituting the solar system. The diameter of the solar system is about thirteen billion (thousand million) kilometers. Light,
which can encircle the earth seven and one-half times per second, traverses the distance from the sun to the earth in a little over eight minutes; it would require about eight and a half hours for light to cross the solar system.

While the solar system sounds big, it is as nothing compared to the distances of the stars. Thus, the nearest star is so remote that light requires four years to traverse that distance. To get an idea of this distance, imagine shrinking the sun to the size of a pea (and all other distances to be reduced correspondingly). On this scale, the nearest star would be about eighty kilometers away.

Our sun is only one of about two hundred billion stars making up a vast pinwheel of stars, gas, and dust. This pinwheel is called the Galaxy. The sun is located about two-thirds of the way from the center to the edge. The diameter of the Galaxy is about twenty-five thousand times the distance to the nearest star. To avoid huge numbers, astronomers have invented a unit of length called the light year. This is the distance light will travel in one year, about ten trillion (thousand billion) kilometers. Thus, the nearest star is about four light years away. The diameter of the Galaxy is about one hundred thousand light years.

Our Galaxy is not the only galaxy in the universe. The nearest large galaxy is the Andromeda galaxy, about two million (thousand thousand) light years distant. And there are many more galaxies, each containing some one hundred billion (thousand million) stars, strewn over the night sky (although the Andromeda galaxy is the only one visible to the unaided eye). It is estimated that about one to a hundred billion galaxies might be detectable with the two hundred inch Palomar telescope. Most of these galaxies appear merely as smudges on a photographic plate.

It is an astonishing fact that as recently as some sixty years ago these numerous smudges of light were not known to be remote stellar systems: one possibility entertained at that time was that they were nebulae within our own Galaxy. In fact, the famous Shapley-Curtis debate, held in 1920, was over this very issue. It was not until early in 1925 that the whole issue was settled by E. P. Hubble's detection, with the then newly completed one hundred inch Mt. Wilson telescope, of Cepheid variables (a kind of pulsating star, see later) in the Andromeda nebula. This discovery placed the Andromeda nebula an appreciable fraction of a million light years away (we shall see later exactly how; this distance is now thought to be about two million light years). This discovery also established this nebula without any reasonable doubt as an independent stellar system, an 'island universe' much like our own Galaxy. Thus was the universe found to be inconceivably vast.

If the quasars (or quasi-stellar objects) are at 'cosmological distances' (which has not yet been established beyond all doubt), then they are the most distant objects in the known universe. Looking like faint, blue stars and exhibiting huge redshifts, these objects may be perhaps up to ten billion light years distant (or more).
II  CEPHEID VARIABLES AS PULSATING STARS

What is a Cepheid variable? Briefly, it is a star that varies in brightness by about a factor of two, over a span of a few days to a few weeks, depending on the star. The 'light curve', a plot of brightness versus time, of a typical Cepheid is shown schematically in Figure 1. The class of variable stars known as Cepheid variables is named after the prototype, Delta Cephei, a star located in the constellation Cepheus. Delta Cephei was the first Cepheid discovered. It was discovered in 1784 by a deaf-mute named John Goodricke, who was nineteen at the time. Delta Cephei has a period (the length of time from, say, one light maximum to the next) of about five and one-third days, and is fairly faint, but visible to the naked eye (of about the fourth magnitude, to use the language of the astronomer).

Cepheid variables are so-called supergiant stars, very large and very luminous. Typically, a Cepheid variable might be some fifty times as large as the sun and several thousand times more luminous. Therefore Cepheids are visible from enormous distances, and have been detected in several dozen of the nearer galaxies. These stars are yellowish, about as hot as the sun is.

Although the light variations were attributed by Goodricke to starspots and rotation, these variations are now thought to be due to pulsation, a rhythmic expansion and contraction, as if the star were 'breathing'. The pulsation hypothesis was first proposed by Ritter in 1879, and was suggested as a serious hypothesis in 1914 by Shapley. The hypothesis was given a firm mathematical foundation in two famous papers by Eddington in 1918. This theory is almost universally accepted today. The variations in the size of the star are not large, only some 5 to 10 per cent in diameter (though, on an absolute scale, these variations are not small — about one and a half million kilometers, roughly the diameter of the sun). Most of the light variation comes from changes in the surface temperature, which varies by about 1000 - 1500°C during the course of a cycle or period.

Cepheid variables are believed to represent only a temporary phase late in the life of stars several times more massive than the sun, kind of like a temporary 'sickness'. When slow stellar evolution gradually changes the state of one of those stars to a state in which the star is 'unstable' against pulsations (see Section V), the star will begin to pulsate essentially spontaneously. It will then continue to pulsate for a total duration of perhaps several million to several hundreds of millions of years, until slow evolution has changed the state of the star so that it has become 'stable' against pulsations again. The star will then gradually stop pulsating over a period of decades or centuries, and will subsequently exist as an ordinary, nonvariable star.
III THE COSMIC DISTANCE SCALE

Why are Cepheids useful as distance indicators? The main reason is that the period of pulsation gives one a pretty good idea as to how bright the star is intrinsically. This relation between the period and the intrinsic brightness of a star is called the period-luminosity relation, to be discussed in more detail in Section IV. The fact that the Cepheids are supergiant stars, and therefore very luminous, and hence visible from great distances, is also very helpful.

Thus, once Cepheids have been identified in some external galaxy and their periods determined (which is fairly easy to do), one has, in principle, a pretty good idea as to the intrinsic brightness of the stars under consideration. By comparing the intrinsic brightness with the apparent brightness of a star, one can work out its distance. A star image on a photographic plate could have been made either by a faint star very close, or by a bright star very far away. (A firefly up close may look as bright as a searchlight many kilometers away.) Therefore the distance and intrinsic brightness of a star both together affect the apparent brightness of a star image. Once the intrinsic brightness of a star is known, the distance (the other factor) can be determined. It is a little like ‘reading the label on the light bulb’ by looking at a distant light bulb through a powerful telescope. The period tells one what the intrinsic brightness of the star is, whereupon its distance (and therefore the distance of the system in which the star is located) can be determined.

The above procedure, of identifying Cepheids and getting their periods, works (i.e., gives distances) for several dozen of the nearer galaxies. The opinion has been expressed by de Vaucouleurs that a safer procedure is to use not only Cepheids, but also other objects, such as novae and ‘RR Lyrae’ stars, to get distances to these nearer galaxies, and this he has done, with results not too different (a factor of about two) from those obtained with Cepheids. For somewhat more remote galaxies, in which the above objects are too faint to be detected, one must make use of intrinsically more luminous ‘distance indicators’ (such as ‘globular clusters’ or ‘H II regions’) for identification. But these more luminous distance indicators will have been ‘calibrated’ on the basis of the nearer galaxies in which Cepheids and other less luminous distance indicators are detectable.

For the most distant galaxies, the galaxies themselves often have to be used as distance indicators. In this method the form of a distant galaxy tells one its approximate intrinsic brightness. Comparison with its apparent brightness then gives its distance. Apparent size also gives a clue as to the distance of a galaxy.

A relatively new method of getting distances of very distant galaxies has recently been used successfully, and will be described more fully in Section VI.

At any rate, the distances of the most remote galaxies can be worked
out in one way or another. But observe that Cepheid variables have played a possibly crucial role in the whole procedure. Indeed, these stars are often regarded as basic ‘yardsticks’ for the measurement of truly great astronomical distances\(^\text{10}\).

At this time let us note a most significant discovery made by Hubble in the late 1920’s\(^\text{3}\) and further refined by Humason and Hubble in the 1930’s. This is that the remote galaxies are all receding from us with velocities that are proportional to their distances — the more distant the galaxy, the greater its velocity of recession! The recession velocities were inferred from Doppler shifts of spectrum lines: the amount of the shift to the red of spectrum lines tells one the recession velocity of the source. This relation of distance to recession velocity is known as the ‘Hubble relation’. The simplest interpretation of this relation is that the entire universe is expanding. This expansion suggests that the universe arose from an ‘explosion’, or ‘big bang’, several billion years ago, from a condition much denser and more compact than the universe now is. But this is another story, and would get us into cosmology.

The velocity-distance relation is shown in Figure 2. Distance is plotted along the horizontal axis, and recession velocity is plotted on the vertical axis.

Nowadays this Hubble relation is turned around, and distances of remote objects are inferred from their recession velocities.

The attempts to determine the value of the ‘Hubble constant’ — the factor of proportionality between distance and recession velocity, or the slope of the line in Figure 2 — are interesting and are discussed in more detail below. The various derived values of this ‘constant’ down through the years also provide a clue as to how great the uncertainties are and how difficult a task its determination is.

The value originally derived by Hubble was 160 km/sec per million light years\(^\text{3}\). This means that the recession velocity increases by 160 km/sec for each additional million (thousand thousand) light years of distance. The reciprocal of this constant gives (in the appropriate units) the approximate time in the past at which the universal expansion began. The original value of the Hubble constant led to a time in the past at which the expansion began of only two billion years. This time was smaller than the age of the earth, so something appeared to be wrong — it did not seem likely that the earth could have been formed before the universe!

This difficulty provided part of the motivation for the development of the ‘steady state’ theory by Bondi, Gold, and Hoyle in the late 1940’s\(^\text{11}\). This theory is very clever and philosophically satisfying. However, it is no longer taken seriously by most cosmologists.

In the late 1940’s Walter Baade was using the then newly operative two-hundred inch Palomar telescope and had taken advantage, with use of the one-hundred inch Mt. Wilson telescope, of the war-time blackouts in the early 1940’s. This work led to his identification of the two stellar
'populations'. In turn, this identification led to the conclusion (announced in 1952\textsuperscript{12}) that the Cepheids were actually four times more luminous than they had been believed to be for the previous forty years or so, and hence that the universe was twice as large\textsuperscript{13}!

In subsequent years work by Sandage, de Vaucouleurs, and others has reduced the accepted value of the Hubble constant still further (or, what is the same thing, increased the cosmic distance scale still more). The value, until recently (say two or three years ago), was about 17 km/sec per million light years — almost a factor of ten smaller than Hubble's original value! This value corresponds to a time in the past at which the expansion began, of about twenty billion years, comfortably larger than the suspected ages of any parts of the universe.

Recently, through the work of de Vaucouleurs and collaborators, and independently through the work of Aaronson, Mould, and Huchra (as will be discussed more fully in Section VI), evidence has accumulated to the effect that the Hubble constant may be somewhat larger (by about a factor of two) than previously suspected, that is, now about 30 km/sec per million light years. This value makes the time since the 'big bang' only about ten billion years.

This time also gives the 'radius of the observable universe', because a galaxy, moving with the speed of light and which started moving away from us ten billion years ago, would just now be observed at a distance of ten billion light years. In other words, this distance of ten billion light years is the distance at which the recession velocity of a galaxy would equal the velocity of light. Since no information can ever reach us from beyond this distance, we may call this distance the 'radius of the observable universe'. The 'cosmic distance scale' would then be a distance like equal to, one-half, or one-third of this radius. Thus, we may conclude that the 'radius of the observable universe' is between ten and twenty billion (thousand million) light years, and the 'cosmic distance scale' must be comparable to this.

We are not concerned here with the value of this distance, which is not the subject of this paper. What is certain is that some quasars and very distant galaxies have extremely large redshifts. For example, the quasar OQ 172 appears to be receding from us at a speed of almost 91\% of the velocity of light\textsuperscript{14}. The galaxy EQ 1305 + 2952 appears to be receding at a speed of about 58\% of the speed of light\textsuperscript{1}.

### IV THE PERIOD-LUMINOSITY RELATION

The famous period-luminosity relation of Cepheids was discovered in 1912 by Henrietta Leavitt of Harvard\textsuperscript{12}. She had been observing the Small Magellanic Cloud, conveniently visible only from the southern hemisphere. All of the stars in this Cloud may be considered at practically the same distance. (It's a little like talking about the distance between
New York and San Francisco. It doesn't matter which street in San Francisco one is talking about; all streets are about the same distance from New York.) She discovered the remarkable fact that the Cepheid variables in this Cloud having longer periods were brighter than those having shorter periods. Since all stars in this Cloud are at very nearly the same distance, then what she was observing must be an intrinsic effect: Cepheids of longer periods must be intrinsically more luminous than Cepheids of shorter periods. While physically incorrect, an analogy might be useful: a tiny penlight could flash on and off more rapidly than a giant searchlight could. (A more physically correct explanation will be given below.) This relation between period and intrinsic brightness is called the 'period-luminosity relation'.

With this period-luminosity relation in hand, astronomers then had a very powerful tool for determining large astronomical distances. It was only necessary to identify Cepheids in other stellar systems and determine their periods. The period-luminosity relation, in principle, gives the intrinsic brightness of the star. A comparison with the star's apparent brightness then determines the distance to the star.

The period-luminosity relation is shown in Figure 3. Essentially, period is plotted along the horizontal axis, and intrinsic brightness along the vertical axis. Thus, given the period of a Cepheid, its intrinsic brightness follows from this relation. A comparison of the star's apparent and intrinsic brightness enables its distance to be worked out.

The period-luminosity-color relation differs from the period-luminosity relation only in the following respect. In this more involved relation specification of the color, as well as of the period, permits a more accurate prediction of the luminosity of the Cepheid. The color specifies essentially where in the instability strip (see Section V) a Cepheid is located. However, in the following we shall speak only of the simpler period-luminosity relation.

In fact this relation had to be calibrated before it could actually be used as a tool for determining stellar distances, that is, numbers had to be put on the axes.

The problem of calibrating the period-luminosity relation constitutes one of the most fascinating chapters in the whole history of astronomy. This story must certainly be very revealing as regards the psychological make-up of astronomers. However, we shall leave this last topic to the psychologists, as this paper is about astronomy, not psychology.

The first attempt at the calibration of this relation was carried out by Hertzsprung in 1913. Hertzsprung made use of the solar motion with respect to other stars and neglected interstellar absorption. (Tiny dust grains between the stars dim the starlight to some extent, just as smoke in a smoke-filled room will dim any light crossing from one side of the room to the other.) His neglect of interstellar absorption did not seem important then, but we now know that it was of the profoundest significance: This neglect (among other things) led to an error in this cali-
bration which, remarkably enough, persisted for approximately the next forty years! In part because of his neglect of interstellar absorption, the intrinsic luminosities were, as we know now, too faint by about a factor of four. Several other calibrations, by other investigations, were carried out independently over the next four decades, with results practically identical to Hertzsprung’s.

Hubble had in the meantime made his epoch-making discovery of the velocity-distance relation (see Section III), and astronomers had begun using the above calibration of the period-luminosity relation to obtain distances of remote galaxies. Thus the error in the original calibration of the Cepheid period-luminosity relation got incorporated into the determination of the cosmic distance scale.

As explained above, it was not until the late 1940’s that Baade, using the then newly operative two hundred inch Palomar telescope, discovered the error which had persisted for the previous forty years in the calibration of the period-luminosity relation. It was then realized that the Cepheids of a given period were actually four times more luminous (intrinsically) than had previously been believed. This change in intrinsic Cepheid brightness caused the cosmic distance scale approximately to double in the early 1950’s. Subsequent work caused this cosmic distance scale to become even larger, until it had attained the value quoted above of ten twenty billion light years.

V WHY DO SOME STARS PULSATE?

The question of what causes some stars to pulsate was a central question in astrophysics for many decades. People such as Schwarzschild, Rosseland, Milne, and Eddington worked on the problem down through the years. Perhaps the most penetrating of this work was that of Eddington. Although we now know that Eddington was incorrect in detail, he did have the correct physical idea. In fact, our present understanding of the causes of stellar pulsation is based to a major extent on Eddington’s fundamental insights.

One important point to keep in mind, a point not realized in Eddington’s time, is that Cepheids are thought to be in a relatively late evolutionary stage. According to current evolutionary theory, such stars are thought to be highly centrally concentrated; that is, most of the mass of the star is concentrated very close to the center. The outer parts of the star, which contain most of the volume, are very tenuous. Consequently, when such a star pulsates, the outer parts move much more violently, and move through a much larger excursion, than do the inner parts. One might say that the inner parts are too ‘heavy’ to pulsate; the pulsations are confined, to a large extent, only to the outer parts of the star. A pulsating star of the Cepheid variety is somewhat analogous to a tapered whip: most of the ‘action’ takes place in the thin parts of the whip. As a result,
the nuclear reactions, which basically 'power' the star, play only a very
minor role (and may, in fact, be ignored altogether) in the pulsation
phenomenon. Thus, any heat absorption or release must rely entirely
on a 'modulation' of the energy flowing through the stellar layers. What
this means is that more or less energy may impinge on the bottom of a
shell than leaves through the top, so that the shell may gain or lose heat.
It might at this point be useful to look in a little more detail at just what
is going on in a pulsating star. At any instant there are at each point
in a star two main forces being felt by the matter: gravity, which tends
to pull the matter inward; and the pressure gradient, which tends to push
the matter outward (since the pressure nearly always increases inward,
this inward increase results in an outward force). It is the balance be-
tween these two forces which will determine the behavior of any given
mass shell in a star. When a shell of matter is too close to the center of
the star, the outward-pushing pressure gradient force is stronger than
the inward-pulling gravitational force, so the matter tends to be pushed
back out. In an ordinary static star, these two forces are almost precisely
balanced. But in a pulsating star one of these two forces is alternately
larger than the other, and so the matter moves outward and inward
rythmically, as in a pendulum. But we all know that a pendulum, if left
to itself, will eventually stop swinging, because of friction. Why doesn't
a star stop pulsating?
To answer this question, we have to look into the matter of the pulsational
stability of a star: i.e., we must investigate whether any small, incipient
pulsations will grow or decay. If a star is pulsationally stable, it will be
an ordinary, nonvariable star, since the decay time of any incipient
pulsations is short compared to the time required for evolution to change
the state of the star appreciably. On the other hand, a pulsationally
unstable star will begin pulsating essentially spontaneously from all the
many small perturbations which are always present. One might say that
a pulsationally unstable star 'wants' to pulsate. Since the rise-time for
the pulsations is relatively short, such a star will be a variable star, per-
haps a Cepheid, for as long as it is pulsationally unstable.
In order to examine the pulsational stability of a star, we must look
upon it as a thermodynamic heat engine, kind of like the internal com-
bustion engine in an automobile. We know that any such heat engine
must operate by absorbing energy when the 'working gases' are com-
pressed, then releasing energy when they are expanded. In this way the
temperature and pressure in the incipiently pulsating star can be a little
larger during the expansion phase than during the contraction phase.
Thus any small, incipient pulsations can get pumped up, or amplified,
and the star can be pulsationally unstable. We might say that, in a
pulsationally unstable, incipiently pulsating star, when it is smallest,
heat leaks out of the interior, where the pulsation amplitude is small;
and is trapped by the regions in the outer parts of the star, where the
pulsation amplitude is large and where the material is appreciably com-
pressed. These outer regions are relatively cool and opaque when the star is smallest. It is as if one were to dump ice cubes into these outer stellar layers, so that they can absorb heat, when the star is smallest. However, in a pulsating star these gains and losses of heat are brought about in a kind of bizarre way by ordinary terrestrial standards. In the motor of an automobile, for example, heat is injected into the cylinders (by the explosion of gasoline-enriched gases) during the compression phase, then removed during the expansion phase. But in a star these heat exchanges must be brought about by a modulation of the energy flowing through the stellar layers. The reason is that, as stated earlier, the nuclear energy sources, which are capable of supplying heat, can play no direct role in the phenomenon. The star accomplishes the desired result by varying the leakage of heat in the right way during the cycle.

The physical agent responsible for producing and maintaining the pulsations of a pulsationally unstable star has been fairly definitely identified. It is the removal by ionization of the second electron from already once-ionized helium, at a depth where this helium is partially twice ionized. This region has come to be called the 'second helium ionization zone'\textsuperscript{18}. The effectiveness of this zone in producing pulsational instability depends crucially on the depth (in mass) of this zone below the stellar surface. This depth, in turn, depends critically on the radius of the star. Thus, when the star reaches the proper radius (which it will have attained through slow evolution), the star becomes pulsationally unstable, and so becomes a pulsating star for a time. This range of conditions under which a star can be pulsationally unstable has been termed the 'instability strip'\textsuperscript{18}.

One interesting fact — confirmed both by theory and observations — is that the pulsation period is inversely proportional to the square root of the mean density of the star. Hence, small, compact stars have shorter pulsation periods than do large, tenuous stars. For the sun, the period would be about an hour if the sun were a pulsating star. For a red giant the period would be several months. For a white dwarf the period would be perhaps about ten seconds. For a neutron star (neutron stars are probably represented by the pulsars\textsuperscript{23}) the period would be less than a thousandth of a second; in other words, the frequency, or 'pitch', of such a star would be a few thousands of cycles per second, i.e., some three octaves above middle C!

The above fact, plus the existence of an 'instability strip' enables us to understand, in a fairly simple fashion, the famous 'period-luminosity relation' referred to earlier, which has played such an important part in determining the distance scale of the universe. This instability strip is characterized by the fact that all stars that are in it have very nearly the same surface temperatures. Therefore a very luminous star (intrinsic-ally) in the instability strip must have a very large surface area, i.e., must be very large. But a large star will have a longer period than will a small star. It follows, then, that the period and luminosity of a pulsating
star should increase together; i.e., a period-luminosity relation should exist. Moreover, detailed calculations lead to fair agreement between the theoretical period-luminosity relation and the empirical one. The fact that theory leads to the expectation of a period-luminosity relation for pulsating stars, which agrees tolerably well with observations, gives us some confidence that our ideas about pulsating stars are basically correct.

VI RECENT DEVELOPMENTS AND CONCLUSIONS

Within the past two or three years a new method of getting distances to very remote galaxies has been developed and applied by Aaronson, Mould, and Huchra to the determination of the cosmic distance scale. This method can be used for galaxies so distant that even the brighter 'distance indicators' (such as 'globular clusters' or 'H II regions', see above) are not visible. It is based on the observation by Tully and Fisher that the width of the hyperfine 21-cm radio emission line of neutral hydrogen is a good indicator of the intrinsic brightness of a galaxy. This width of the 21-cm line is a direct indication of the rotation velocity of the galaxy. This rotation velocity, in turn, is determined by the total mass of the galaxy: the higher the mass of the galaxy, the greater is the rotation velocity, and hence the wider is the 21-cm radio line (the centrifugal force must be larger to counterbalance the stronger gravitational attraction of a more massive galaxy). Finally, the ratio of total mass to total luminosity is constant from one galaxy to another, at least for the kinds of galaxies to which the method applies. Hence, the more massive a galaxy, the brighter it is intrinsically. Once calibrated, this 21-cm line width-intrinsic brightness relation serves as a powerful tool for getting distances of remote galaxies. Aaronson, Huchra, and Mould found that the correlation of 21-cm line width with luminosity was better if the 'luminosity' was the infrared luminosity of a galaxy (i.e., the intrinsic brightness in the infrared part of the spectrum).

This work suggests that the Hubble constant might be about 30 km/sec per million light years — roughly twice the value that has been generally accepted for the past decade or so. If this value is correct, then the cosmic distance scale is only about half what it was before. As stated above, this value makes the time since the 'big bang' (the 'age of the universe') only about ten billion (thousand million) years, once again perhaps a little uncomfortably short.

The above value is also in good agreement with one recently obtained by de Vaucouleurs and collaborators.

The interpretation provided by Aaronson, Mould, and Huchra and by de Vaucouleurs and Bollinger for the larger value of the Hubble constant obtained in these recent works is the following. A giant cluster of galaxies in the direction of the constellation Virgo (the Virgo cluster) is slowing
down the expansion rate of the nearer galaxies (those in the 'local super-cluster'\textsuperscript{27}) out to a distance of perhaps 150 million (thousand thousand) light years, presumably by means of gravitational attraction. It is this 'local' slowing down of the expansion rate which had led, according to these authors, to a too-small value of the Hubble constant in the past. The newer, larger value is supposed to apply to all of the more distant parts of the universe.

This larger value, however, is not accepted by all workers in the field. It therefore appears that the exact value of the Hubble constant is still in a state of controversy. It is our feeling that factors of two are not a tremendous matter for concern. What seems relatively certain is that the 'radius of the observable universe' is somewhere between ten and twenty billion light years. This statement also applies approximately to the cosmic distance scale. Therefore the 'age of the universe' is probably somewhere between ten and twenty billion years.

Within the area of pulsating stars, there have in recent years been several additions to the class: for example, variable white dwarfs ('ZZ Ceti stars'\textsuperscript{28}); certain very hot, luminous stars (the 'line profile variable B stars'\textsuperscript{29}); and possibly even the sun, which may be undergoing small oscillations\textsuperscript{30}. However, to the best of this author's knowledge, there has been nothing of late to cause a significant change in our basic ideas as to the causes of stellar pulsation. There are, to be sure, some troublesome features. For example, pulsation theory and stellar evolution theory seem to disagree (by factors like two or three) in some cases regarding the masses of Cepheids. Also, nonradial oscillations, characterized by different parts of the stellar surface moving out of phase with one another, seem to be rather prevalent in nature. But even these nonradial oscillations seem to be 'driven' in most cases by the same sorts of mechanisms that are responsible for the pulsations of Cepheids. These features may be considered details which experts in the field can (and will, no doubt!) worry about.

However, it is probably safe to say that understanding the causes of the pulsations of Cepheid variables, and also realizing the role that these stars have played in helping us to know our place in the cosmos, have enriched our intellectual experience.

J. P. C.

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BIBLIOGRAPHY AND NOTES

1. A good and very readable account of the methods astronomers use to determine cosmic distances is by J. S. Trenn, in the July-August, 1979, issue of Mercury.

2. A popular account of this debate has been provided by D. Seely and R. Berendzen, in the July-August, 1978, issue of Mercury. Additional information regarding this debate may be found in N. A. Hetherington, A. S. P. Leaflet No. 490 (1970).

3. The original announcement of Hubble's discovery on January 1, 1925 has been described by R. Berendzen and M. Horskin, in A.S.P. Leaflet No. 50 (1971). For a more technical description of Hubble's work, see e.g., E. Hubble, Proc. Nat. Acad. Sci., 15 (1929), 168.


5. A. Ritter, Wiedemanns Annalen, 8 (1879), 172.


17. E. Herzberg, J. N., 196 (1913), 291.


A largely physical description of the causes of stellar pulsation in common types of variable stars may be found in J. P. Cox, Theory of Stellar Pulsation, Princeton University Press, Princeton, Chap. 10, 1980.

The evolutionary stage of Cepheids has been discussed by J. P. Cox, Rep. Prog. Phys., 37 (1974), 563, Section 9.


The 'light curve' (schematic) of a typical Cepheid. The period is the duration of time between two successive maxima (as shown) or minima (from Galaxies and Quasars by William J. Kaufmann, III, W. H. Freeman and Co., Copyright © 1979).

Figure 2

The velocity-distance relation of distant galaxies. The speed is the recession velocity as determined by the Doppler shift of spectrum lines (from Galaxies and Quasars, by William J. Kaufmann, III, W.H. Freeman and Co., Copyright © 1979).
