

Cosmic Distances and QSO's

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The next time you are out on a clear night, look around the sky. The brightest objects you see are likely to be the Moon and a planet or two; perhaps Jupiter will stand out. The other objects visible are stars in our galaxy.

A notable exception, if you are in a dark place and it is the right time of year, may be the oval blur which was long known as the Great nebula in Andromeda but is now more correctly called the Andromeda galaxy. Binoculars may help you find it.

The planets do not appear to be very different from the brighter stars, yet, as you may know, the stars are millions of times farther away. You may also be aware that the planets are hundreds to thousands of times more distant than the Moon.

Do you wonder how these distances have been determined? Certainly not with a tape measure. How reliable are they? Did you know that the estimated distance to the Andromeda Galaxy has almost tripled since it was first measured, just over half a century ago?

Let us examine the methods which have been used to measure distances in the universe.

Distances Within the Solar System

It is not surprising that the first distance to be determined was that of our nearest neighbor in space, the Moon. More than two thousand years ago, Ptolemy measured this distance by triangulation (also called parallax). He measured the angle formed by a point on the Moon and two points on the Earth's surface and "solved" the triangle by trigonometry.

You may wonder how Ptolemy managed to observe from two widely separated points on Earth. He simply waited a few hours, and the Earth's rotation carried him around to the



Figure 1. The Hyades (photo by Miriam Carolin, Sonoma State University Observatory)

other side.

Ptolemy found, correctly, that the Moon's distance is fifty-nine times the Earth's radius. Today this distance, approximately 380,000 kilometers or 240,000 miles, is known to within a few centimeters. The greatest precision is obtained by measuring the round trip travel time of laser pulses sent from Earth to reflectors placed on the Moon by astronauts.

Many centuries were to pass before the distances to the planets could be determined. It was Copernicus, in 1543, who made the breakthrough. His famous book, *On Revolutions*, did more than just move the center of the universe from the Earth to the Sun; it also provided a scale model of the solar system. From the observed motions of the planets and geometry, the Polish canon computed the *relative* distances of the planets and Sun.

Copernicus found the average distances of the planets from the Sun in terms of the average distance between the Earth and the Sun, called the astronomical unit (A.U.); this turned out to be 0.36 A.U. for Mercury, 0.72 for Venus, 1.5 for Mars, 5 for Jupiter and 9 for Saturn. All that was needed was one direct measurement to set the scale.

This scale, which would allow us to convert from astronomical units to kilometers, has been measured with increasing precision over the past four hundred years. Today, an A.U. is known to be 149,597,870 km, or approximately 93 million miles. The best determination comes from the use of radar; echoes of radar signals have actually been detected from as far away as Saturn, nearly a billion miles away.

But nowadays we know that our solar system is, in a sense, merely our back yard. How did we obtain distances to the much more remote stars?

Stellar Distances

For centuries astronomers tried to measure stellar distances by trigonometric parallax. If the Earth actually moves around the Sun, then over the course of the year the nearby stars should show apparent motions with respect to the more distant ones, just as a pencil held at arm's length shows a shift relative to the background when viewed from one eye and then the other. The greatest pre-telescope observer, Tycho Brahe of Denmark, was able to measure angular changes as small as one minute of arc, yet he could detect no such motion. He concluded that the Earth does not move.

It was only 140 years ago that three different men, in three different countries, finally succeeded in measuring the yearly parallax of shift of three of the nearest stars. The first was Bessel, in Prussia, who measured the distance to 61 Cygni, a dim star suspected to be close to us because of its relatively large non-parallax motion across the sky. The others were Henderson, who observed Alpha Centauri from the Cape of Good Hope, and Struve, of Russia, who measured the shift of the bright star Vega.

MERCURY — The Journal of the Astronomical Society of the Pacific (ISSN 0047-6773) is published bimonthly by the Astronomical Society of the Pacific, 1290 24th Ave., San Francisco, CA 94122. Second class postage paid at San Francisco and at additional mailing offices. POSTMASTER: Send address changes to: *Mercury*, A.S.P., 1290 24th Ave., San Francisco, CA 94122.

The parallax of a star is actually the angle through which the star appears to move as the Earth completes half of its annual orbit. Since the more distant stars will show a smaller parallax shift, the distance of the star is inversely proportional to this angle. Astronomers make things simple by measuring distances in *parsecs*, which are defined as the distance at which a star would have a parallax shift of one second of arc in each direction. One parsec turns out to be 206,265 astronomical units, or 3.26 light years. The nearest neighbor star to the Sun, Alpha Centauri, is one and one-third parsecs distant.

By now a few thousand of the nearest stars have had their distances determined by this direct geometric method. The brightest stars are not, in general, the nearest. Of the twenty brightest stars in the sky, only Alpha Centauri, Sirius, and Procyon are within five parsecs of the Sun. On the other hand, most of the nearest stars are intrinsically so dim that they cannot even be seen without binoculars or small telescopes.

If only a small fraction of the stars are near enough to have measurable parallaxes, and these do not even include some of the brightest stars, what do we do next?

One method of measuring the distances to more distant stars is based on the motions of stars in a nearby star cluster, such as the Hyades in the constellation of Taurus (Figure 1). Since our solar system is moving away from this cluster, all of its stars show motion toward a point on the celestial sphere, in a direction opposite that in which the solar system is moving.

If we assume that each star in the cluster is moving in the direction of this point at infinity, we can break up the star's motion into components along and perpendicular to our line of sight. The component along our line of sight can be measured directly in kilometers per second from the Doppler shift of the lines in the star's spectrum. Knowing the direction in which the star is moving, the component across the line of sight can then be determined, in kilometers per second, from geometry. It can also be measured, in seconds of arc per year (this is called the *proper motion*) from photographs taken years apart. Combining these two independent measurements yields the distance to

the cluster.

We shall see that the recent revision of this distance changed the whole scale of the universe by nearly ten percent.

The reason this cluster is so important is that it provides us with a large number of stars with known distances. These stars can be plotted on a graph of luminosity versus spectral class, the well-known Hertzsprung-Russell (H-R) diagram.¹ Once the diagram is calibrated, with stars of known distance, it becomes possible to determine the distances of other stars by plotting their positions on the graph.

Since the basic position of the majority of stars in any cluster should be the same on such a graph, another cluster, of unknown distance, can be plotted on the H-R diagram, and the position of its stars adjusted so that its main sequence (the diagonal line where most stars fall on the diagram) coincides with that of the Hyades. The amount of adjustment necessary yields the distance to the cluster, in terms of the distance to the Hyades.

For example, if the main sequence stars in the Hyades appear 100 times as bright as similar stars in the other cluster, then that cluster is ten times as distant as the Hyades.²

A star need not be in a cluster for its distance to be determined by this method. Once its spectrum is measured and classified, it can be placed on the H-R diagram and its luminosity estimated. This was done for an enormous number of stars in the early years of this century. Foremost among the classifiers of stellar spectra was Annie J. Cannon, of Harvard College Observatory, who classified more than 300,000 stars.

Cepheid Variables

It was in 1912 that another of the Harvard astronomers, Henrietta Leavitt, made an important discovery. She was studying photographs made in South America of Cepheid variable stars in the Small Magellanic cloud. These are stars which regularly grow brighter and dimmer with a period of a few days or weeks.³ Leavitt discovered a relationship between the periods of variations and the underlying luminosities of these stars. Of course she did not know their true luminosities, as the distance to the Small Magellanic cloud was unknown. But all that was needed was the dis-



Figure 2. Annie J. Cannon and Henrietta Leavitt (from Shapley, Harlow, *Through Rugged Ways to the Stars*, Charles Scribner's Sons, New York 1969, reprinted courtesy of Willis H. Shapley.)

tance of one Cepheid to calibrate the scale. Then the Cepheids, which are very bright stars, could be used as distance indicators.

Hertzsprung, Russell, and others used statistical methods to find the average luminosity of Cepheids, and then Harlow Shapley used Leavitt's relationship to measure the distances to the globular clusters. The result of his work was another Copernican revolution: Copernicus had showed that the Earth was not at the center of the the solar system. Now Shapley showed that the Sun was not at the center of the system of stars. The globular clusters surround the Galaxy, a disk some 100,000 light years across and the Sun is off to one side.

1. An H-R diagram is depicted on p. 126 of the Nov/Dec 1978 *Mercury*. It is also available on a new A.S.P. T-Shirt, as described in the *Selectory* in this issue. — Ed.

2. This calculation follows from the fact that the intensity of light falls off as the *square* of the distance. — Ed.

3. See the article on variable stars by John Percy in the May/June 1979 *Mercury*. — Ed.

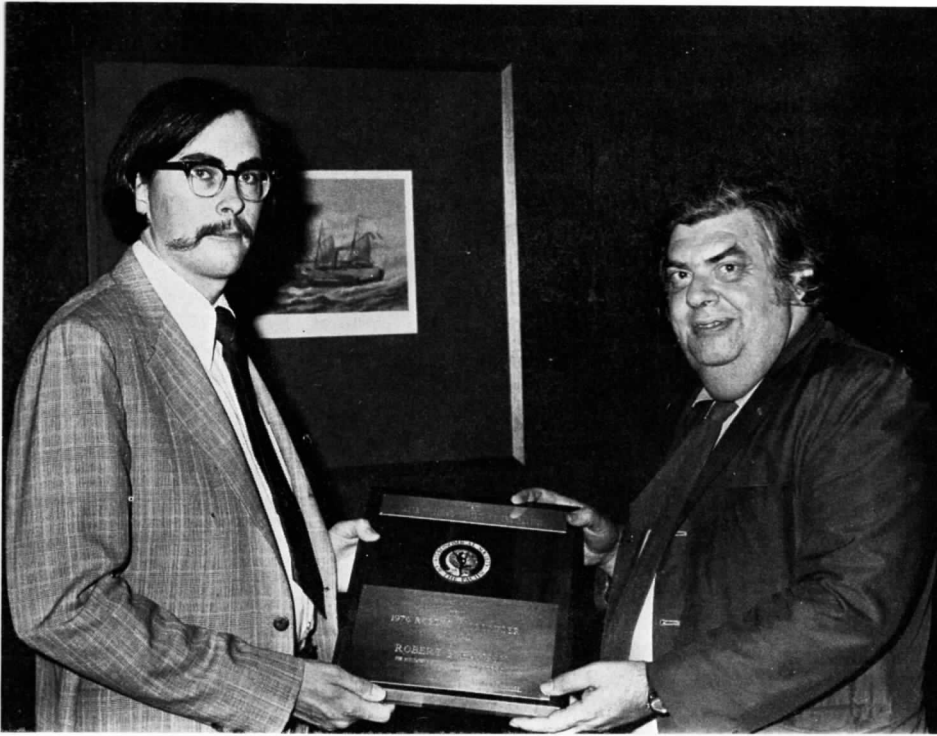


Figure 3. Robert Hanson accepts the 1976 A.S.P. Trumpler Award from then-president Geoffrey Burbidge.

Shapley, however, made an important error regarding the fuzzy objects which were then called spiral nebulae. He thought they were small, nearby objects, either satellites of the Milky Way or perhaps objects which filled the space through which the Galaxy moved.⁴

It was Edwin Hubble, just over fifty years ago, who showed that the spirals were actually external galaxies comparable to the Milky Way. He did this by finding Cepheid variables in some of the nearer spirals, most notably the great one in Andromeda. He found this object to be 285,000 parsecs, or about 900,000 light years, distant. (Today it is believed to be about two and a half times as far away.)

Hubble and Milton Humason went on to measure the distances of more than thirty galaxies in this manner. They then proceeded to measure more distant ones by using their brightest stars as *standard candles*. They reasoned that if the brightest star in each galaxy had about the same intrinsic brightness, then the dimmer such a star looked in a given galaxy, the more distant that system had to be.

Finally, they used the brightest galaxies in clusters as distance indica-

tors. On the average, at least, the dimmer galaxies should be farther away.

From all this work they were able to make a most important discovery: the velocity-distance relation, now usually called the "Hubble Law." It states that all but the nearest galaxies are receding from us and that the velocities of recession are proportional to their distances.⁵ The velocities of recession are calculated from the *redshifts*, or fractional increases in wavelength of the spectral lines. Knowing the velocity, astronomers can then use Hubble's Law to calculate the distance to galaxies so remote that neither individual stars or clusters can be discerned in them.

With long time-exposures, large modern telescopes can detect enormous numbers of galaxies. It is estimated from counts of a few random areas that if one could spend the necessary thousands of years photographing each section of the sky, then more than a billion of them could be detected. Indeed, deep photographs show more galaxies than stars! Most of these are too faint for detailed examination, but the dimmer ones do show larger redshifts, indicating greater velocities of recession. They

appear to obey the Hubble Law. Thus today a galaxy with a certain measured redshift is taken to be at the distance given by this law.

For many years, from 1960 until the mid-1970's, the most distant galaxy known was 3C 295, the radio galaxy whose redshift was measured by Rudolph Minkowski on the last night he was allowed to use the Hale telescope before compulsory retirement at age 65. Its redshift of 0.46 corresponds to a distance of 2 billion parsecs or 6.5 billion light years. In recent years the use of electronic photon detectors on large telescopes has allowed Hyron Spinrad and others to measure several galaxies with redshifts of 0.6, 0.7 and even higher. One galaxy, called C1 1305+2952, has a redshift of 0.947.

Deviations from the Hubble Law, expected for very distant galaxies, should in principle allow us to determine the geometry, and hence the fate, of the universe. However, there are great problems in determining the effects of the evolution of galaxies.⁶ Let us return therefore to the measurement of distances.

Revisions in the Scale

The distance scale built up until now has been revised three times. In the 1930's, Robert Trumpler showed conclusively that there is an "interstellar smog." Thus some of the dimming of stars is caused by the passage of their light through dust in our galaxy rather than by distance as previously assumed. In addition, it was shown in the 1940's that there are actually two kinds of Cepheid variables, with different period-luminosity relations. Both of these discoveries increased distance estimates.

The third revision came in 1976 when Robert Hanson, a graduate student at the University of California, Santa Cruz, showed by the old-fashioned measurement of proper motions that the Hyades cluster is

4. A famous debate on this subject between Shapley and H.D. Curtis was described in the Jul/Aug 1978 issue of *Mercury*. — Ed.

5. The equation is written $V = Hd$, where V is the velocity, d is the distance and H is called Hubble's constant.

6. See "Cosmology — The Origin and Evolution of the Universe" in *Mercury* May/June 1978. — Ed.

actually farther away than previously thought. Since all distances are built up from the location of the main sequence of this nearest cluster, the demonstration that it is 144 light years away rather than 132 was sufficient to increase the known size of the universe nearly 10%!⁷ Another way of stating this is that the best estimate of the Hubble constant dropped from 55 kilometers per second per million parsecs to 50. (The earlier revisions had brought it down from Hubble's original value of more than 500.)

Quasars

What are quasars? In short, we don't know. These *quasi-stellar objects* (a name preferred by many of the workers in the field) look much like ordinary stars. It is only when one examines their spectra that their strange properties appear.⁸

These objects, which look like blue stars, have the largest redshifts known. They range up to 350% for two discovered in 1973, with many shifted by 100 to 200%.⁹ With these, we are back in the position of the astronomers of 150 years ago looking at the stars, or those of 60 years ago, looking at the spiral nebulae. We don't know how far away they are; we really do not know much about them at all.

In the sixteen years since the quasar's large redshifts were discovered by Maarten Schmidt at Caltech, there has been no lack of effort by theorists to explain the QSOs. The most natural explanation to most astronomers and physicists is that the redshifts are Doppler shifts, like those of the galaxies. One of the best reasons for this assumption is that there is no other explanation. Gravitational redshifts¹⁰ have been shown to be unlikely and no other causes of redshifts are known.

Once we assume the redshifts are Doppler shifts, we have the problem that the QSOs are all moving away at speeds comparable to the speed of light, over 90% for two of them. Why are they moving away so fast? If they are nearby, they must have been ejected by our own or other nearby galaxies. The problem with this is that there are too many quasars. A recent estimate gives seven per square degree in the sky brighter than twentieth magnitude. Even though we do not know their masses, it seems that too violent an explosion is required in

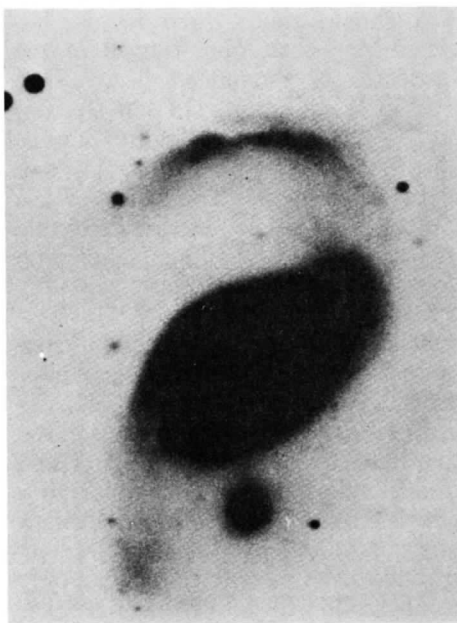


Figure 4. Galaxy NGC 4319, redshift 0.006 and companion quasar Markarian 205, redshift 0.07 (Arp, H., *Astrophysical Letters* 9,1 (1971).

this part of the universe.

There is also the problem that QSOs would have to be ejected from other galaxies as well, and some should be coming our way. Yet, no blue shifts have been found.

Thus it is not surprising that most astronomers have made the assumption that the quasars are obeying the Hubble Law, sharing in the expansion of the universe. This, of course, places many of them out beyond the most remote galaxies yet detected, and leads to newspaper headlines: "Most distant object discovered" or "Oldest thing in the universe found." Since the quasars appear to be up to ten billion light years distant, it follows that their light has been traveling for as much as ten billion years, and we see them as they were when the universe was young. In fact, one of the arguments for an evolving universe is that there are too many quasars with large redshifts and too few with small ones. This implies that the density of quasars in the universe was greater some billions of years ago than it is now. Hence, the universe is changing.

It is popular to believe that the quasars are some kind of early stage of galaxies. It is even thought that the Seyfert galaxies, with their bright star-

like nuclei, provide the "missing link."

So why isn't everyone happy, except, of course, those cosmologists who do not accept the idea of an evolving universe? The problem is that the quasars appear to be too bright to be so far away. Putting in the distances given by the Hubble Law, and the apparent brightnesses, and using the inverse square law, we find that the quasars are 100 to 1000 times as bright as the brightest galaxies.

You might say that perhaps quasars are bright for a short time and then evolve into galaxies. While some people do say this, there is the additional problem that the quasars are known to be small. They vary in brightness in times as short as months. This means they cannot be more than light months across, a diameter not much bigger than the solar system.

The arguments have raged for more than a decade now. The steady state cosmologists, especially Geoffrey Burbidge, have argued that the quasars must be nearby, and that the redshifts cannot be cosmological Doppler shifts. Is any progress being made?

On several occasions each side has claimed victory. For example, in 1973, it was asserted that quasars, like galaxies, obey a Hubble Law: the dimmer ones have the larger redshifts. While a plot of redshift versus magnitude (dimness) for a large sample of quasars does not show this relationship, G. Setti and A. Woltjer found one by dividing quasars into three groups: those with no radio emission, those with flat radio spectra and those with steep radio spectra. Only in the third group were they able to find a tendency towards larger redshifts for dimmer objects.

Others have said that the only reliable way to determine the distances to these mysterious objects is to show

7. For this work Dr. Hanson received the 1976 Robert J. Trumpler award of the A.S.P. — Ed.

8. See the article on quasars by H.E. Smith in the Mar/Apr 1978 issue of *Mercury*. — Ed.

9. These redshifts can be greater than 100% because at such high speeds Einstein's theory of relativity comes into play, as explained on p. 27 of the Mar/Apr 1978 *Mercury*.

10. Gravitational redshift is the change in the wavelength of radiation in a gravitational field. It is only detectable when the source has a very strong gravitational field. — Ed.

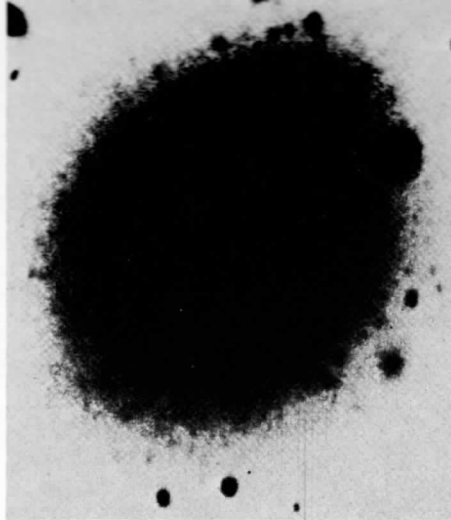


Figure 5. Galaxy NGC 1199, and compact companion. (Arp, H., *Astrophysical Journal* 220, 401 (1978). (Courtesy of H. Arp and the *Astrophysical Journal*, published by U. of Chicago Press, © 1978, AAS.)

Institute for Advanced Study, was held in Washington, D.C. in December 1972.¹¹ This recalls the famous debate between Harlow Shapley and Heber Curtis on "The Scale of the Universe." Both debates are enjoyable to read, but observations rather than debates are needed to settle scientific controversies.

In 1978 the situation became even more exciting. In March, Arp published an astonishing photo (Figure 5) in the *Astrophysical Journal*. It shows an elliptical galaxy, NGC 1199, with a small, compact object apparently *silhouetted in front* of it. Notice the dark ring (light in this negative print) around the small object. This can only be absorption of light from the larger galaxy by a shell of gas and dust around the small object. Arp presents a detailed discussion showing that everything is consistent with this hypothesis. Yet the redshift of the small object corresponds to a velocity of over 13,000 km/sec while that of the elliptical galaxy implies that it is receding at only 2600 km/sec. Arp concludes his paper:

This is interpreted to be another example of a young, compact object recently ejected from the E galaxy and having a moderate component of intrinsic, non-Doppler redshift.

Shortly afterward, Alan Stockton of the University of Hawaii published an article in the same journal purporting to prove that the redshifts of the quasars *are* cosmological.

What Stockton did was to survey a complete sample of quasars in a certain range of magnitude, redshift, and location in the sky. He chose all those from a certain catalog which were visible from Hawaii and had redshifts low enough that galaxies with the same redshifts should be visible. In other words, these are relatively low redshift quasars, with redshifts of 0.2 to 0.44. For each quasar, he measured the spectra of all galaxies within 45 seconds of arc in the sky. He was able to obtain redshifts for 25 of the 29 galaxies within 17 fields. Thirteen of these, in eight of the fields, had redshifts essentially the same as those of the nearby quasars. This implies that the

fact due to their motion away from us. He states that:

The probability that this number of agreements is due to chance has been evaluated from the observed distribution function with redshift of the galaxy sample, and has been shown to be less than 1.5×10^{-6} , making the cosmological nature of QSO redshifts virtually certain.

By now you should be confused. Who is right? Are the quasars sharing in the expansion of the universe, making them the most distant objects detected and puzzling only because of their enormous energy outputs, or are they much nearer, teasing us with redshifts which are not due to velocities but to some "new physics" yet to be discovered?

I don't know, but I believe that, as in the case of the stars a few centuries ago and the spiral nebulae a few decades ago, their nature will become understandable only after their distances are determined. ■

Editor's note: Dr. Tenn was one of the hosts for the 1979 summer meeting of the A.S.P., which included a symposium on this subject. In our next issue he will describe the discussion at the meeting and bring us up to date on the quasar controversy.

Recommended for Further Reading

Whitney, C.A., *The Discovery of Our Galaxy* (Knopf, New York, 1971). Excellent history.

Shipman, H.L., *Black Holes, Quasars, and the Universe* (Houghton Mifflin, Boston, 1976). Recent developments.

11. The debate is available as a book entitled *The Redshift Controversy* by G. Field, et. al. (Benjamin, 1973).

that they are attached to objects whose distances are known. The only other objects around are the galaxies, so great efforts have been made to photograph quasars near galaxies and to find links. Foremost in this field has been Halton C. Arp of the Hale Observatories. Over the last decade he has photographed a great number of peculiar objects and claimed to see connections between objects of different redshifts.

Figure 4, for example, shows a galaxy, NGC 4319, with a redshift of 0.006 and a quasar, Markarian 205, with a redshift of 0.07. If both obey the Hubble Law, the quasar is more than ten times as far away as the galaxy, and their appearance in the same part of the sky is purely a coincidence, like the case of Alcor and Mizar, the well-known double star in the handle of the Big Dipper. In the picture, which is greatly over-exposed and taken through a filter, Arp sees a physical link.

Arp believes that quasars are ejected from galaxies, and that they have redshifts which have nothing to do with velocity but rather are intrinsic and change with time. He has presented a great number of examples of ejection in a series of papers over the past dozen years.