

THE REDSHIFT CONTROVERSY IN QUASAR ASTRONOMY

Jayant V. Narlikar*

Tata Institute of Fundamental Research,
Bombay 400 005

I. INTRODUCTION

Like other branches of science astronomy has had its share of controversies. The most well known of these is of course the controversy between the geocentric and the heliocentric theories of our Solar System, a controversy which involved Copernicus and Galileo against the Aristotelian view supported by the Establishment. At the beginning of the present century, a minority led by R.A. Proctor held the view that our universe was not confined to the Milky Way System but extended well beyond it. Again, this view was in conflict with the Establishment view that all the observable universe was part of the Milky Way. During the 1920's Eddington argued that stars derived their energy of radiation from the store of nuclear energy, a view which was considered untenable by the atomic physicists of the day.

Progress of science and observational techniques have helped to resolve these controversies. However, new observations lead to new discoveries and to fresh controversies when it comes to interpreting those discoveries. Quasars furnish a classic example of how a cosmological controversy originates and evolves.

The quasars were first discovered in 1963 as a result of successful cooperation between the radio and optical astronomers. The positions of two radio sources 3C 48 and 3C 273 (the 48th and 273rd sources in the 3rd Cambridge Catalogue) were measured accurately by astronomers in U. K. and Australia. When the optical astronomers at the Hale Observatories examined the same positions at visual wavelengths, they found objects which resembled stars. Indeed, the early interpretation of these sources was that they were radio stars. The objects had compact starlike appearance and their spectra showed emission lines as in the spectra of stars.

The unusual aspect of these newly discovered objects became evident soon afterwards. Their spectra showed substantial *redshifts*.

The astronomer defines redshift in the following way. Suppose we identify a certain line in the spectrum of the object with a well known atomic transition. Atomic physics then tells us that the wavelength of the line should have a certain value λ_0 . If the observed line does not have the expected wavelength λ_0 , but has a different wavelength λ , then the quantity

$$z = (\lambda - \lambda_0) / \lambda_0 \quad (1)$$

is called the **spectral shift** of the line. If $z > 0$ the shift is known as redshift and if $z < 0$ it is known as blueshift. If all the observed lines in the spectrum show the same shift, we say that the entire spectrum has shifted. If $z > 0$ the shift is towards the long wavelength (red) end of the visual spectrum while if $z < 0$ the shift is towards the short wavelength (blue) end.

For 3C-273 the redshift was $z = 0.158$ while for 3C-48 it was $z = 0.367$. What was the cause of these redshifts? The controversy concerns this question and to understand the background of the various arguments let us first enumerate the possible causes of redshift known to the physicist.

II. THE THREE TYPES OF REDSHIFTS.

The physicist is most familiar with the **Doppler** shift which arises when there is relative motion between the source of light and the observer. In Figure 1 we see a source S moving with speed V relative to the observer O, in a direction making an angle θ with the line of sight OS. Special relativity then shows that

$$1 + z = \frac{1 + \frac{V \cos \theta}{c}}{\sqrt{1 - \frac{V^2}{c^2}}} \quad (2)$$

where c = speed of light. From (2) we note that the source is seen blueshifted or redshifted according as

$$\frac{V}{c} \cos \theta < \text{or} > \sqrt{1 - \frac{V^2}{c^2}} - 1. \quad (3)$$

A second interpretation of spectral shift comes from general relativity. Imagine a source of light S

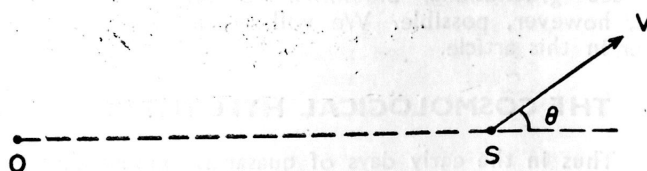


Fig. 1 Doppler shift arises when there is relative motion between the source and the observer, as in the figure above.

* Visiting Scientist at the Kitt Peak National Observatory from March 1 to April 17, 1982

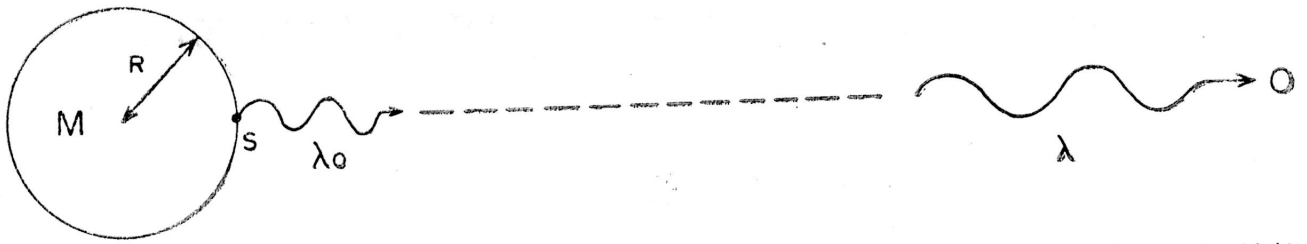


Fig. 2 Light leaving the strong gravitational field of the massive object, becomes redshifted when it reaches a region of weak gravitational field.

located on the surface of a massive object of mass M and radius R . Suppose the observer O (see Figure 2) is located very far away from M . Then the light emitted by S is seen redshifted by O with

$$1 + z = \frac{1}{(1 - 2GM/c^2 R)} \quad (4)$$

Note that if O were to send light received by S , it would be blueshifted with

$$1 + z = \sqrt{1 - \frac{2GM}{c^2 R}} \quad (5)$$

Thus redshift or blueshift arises when light travels from strong to weak gravitational field or vice versa.

The third interpretation of redshift comes from cosmology. Current ideas on cosmology tell us that the universe is expanding. We may visualize this statement by imagining the universe as a framework with galaxies at the vertices (see Figure 3). This framework expands uniformly everywhere so that we may associate the expansion with a scale factor $Q(t)$ which increases steadily with time t . Viewed from any galaxy this expansion gives the effect of recession of all other galaxies. Suppose light left from a remote galaxy S at time t_1 and reached an observer O at time t_0 . Then O will find the light redshifted with

$$1 + z = \frac{Q(t_0)}{Q(t_1)} \quad (6)$$

We will refer to these three causes of spectral shift by the adjectives 'Doppler', 'gravitational' and 'cosmological' respectively. Note that so long as the universe has been continually expanding, there can be no cosmological blueshift. Similarly, since we are located in a region of weak gravitational field, we do not expect to see gravitational blueshifts. Doppler blueshifts are, however, possible. We will return to this point later in this article.

III. THE COSMOLOGICAL HYPOTHESIS.

Thus in the early days of quasar astronomy, there were three possible interpretations available for explaining the observed redshifts. The astronomers were aware of redshifts of galaxies as high as 0.46 and these

redshifts were due to the expansion of the universe. The Doppler or gravitational redshifts of stars in our Galaxy did not exceed 0.001. In fact no examples of astronomical objects with high Doppler or gravitational redshifts were known. Astronomers therefore naturally preferred to interpret the quasar redshifts as cosmological.

The cosmological redshift of an object is related to its distance from us according to a law discovered by Edwin Hubble in 1929. Hubble's law is simply stated in the following form:

$$z = \frac{H_0}{c} D, \quad H_0 = \text{constant} \quad (7)$$

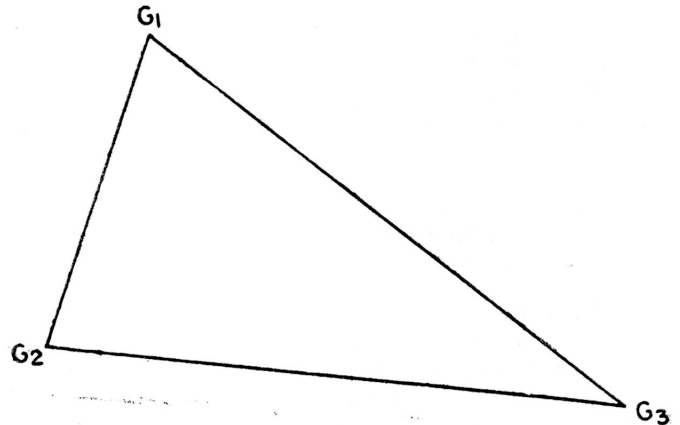
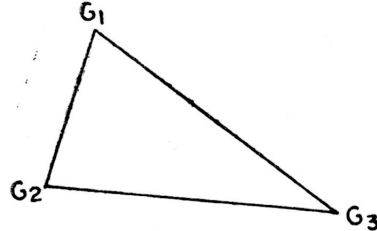


Fig. 3 A triangle of any three galaxies G_1, G_2, G_3 in the expanding universe, would grow in size with time while retaining its shape. When viewed from any vertex of the triangle, the other vertices appear to recede.

where D is the distance of the object from us. Hubble's law was originally obtained on empirical grounds but it follows naturally from the expanding cosmological models. The Hubble constant H_0 is related to the scale function $Q(t)$ by the following formula :

$$H_0 = \left[\frac{1}{Q(t)} \frac{dQ}{dt} \right]_{t=t_0} \quad (8)$$

where the right hand side is evaluated at the present epoch. H_0^{-1} has the dimensions of time and its value lies in the range ~ 10 -20 billion years.

Hubble's observations extended upto small redshifts with $z < 0.1$. Later observations have given support to the law at higher redshifts. Different cosmological models predict different functional behaviour for z and D ; however, all agree with (7) in the limit of small z . Attempts to distinguish between the predictions of the different models by measuring the z - D relationship at redshifts upto 0.3-0.4 for galaxies have so far proved futile (see Figure 4).

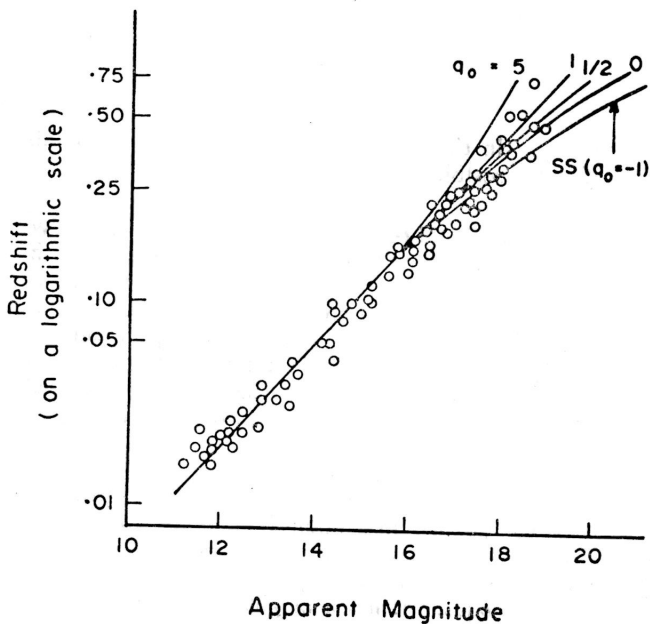


Fig. 4 The Hubble plot for more remote galaxies together with the theoretical curves of a number of cosmological models. The observational points are based on the work of J. Kristian, A. Sandage, and J.A. Westphal, *Astrophys. J.*, **221**, 383 (1978). The visual magnitude is proportional to the logarithm of flux received from the galaxy. Given the scatter in the Hubble plot it is difficult to single out any particular model as the right one.

However, taking the Hubble law (7) as applying to quasars, we see that they must be very distant objects. For example, with $H_0^{-1} = 10$ billion years, the quasar 3C-273 must be 158 million light years away. Yet it was bright enough and compact enough to be

mistaken for a star in the Galaxy with a typical distance of a few thousand light years. Indeed, if we use the cosmological redshift interpretation, the quasar 3C-273 must be so powerful that its energy output exceeds that of a typical galaxy !

This is the essence of what has become known as the **cosmological hypothesis**. This hypothesis states that quasars are very far away, at distances corresponding to their Hubble-law distances and that therefore they are very powerful yet compact radiators of energy. The quasar 0Q-172 with the largest known redshift of 3.53 must be the farthest object in the universe.

If, on the other hand the cosmological hypothesis does not hold for quasars, then their redshifts are not distance indicators. The quasars can then be considerably closer to us and correspondingly they are less powerful radiators.

Before coming to the redshift controversy we will briefly outline the non-cosmological alternatives.

IV. NON-COSMOLOGICAL REDSHIFTS.

In 1964 J. Terrell [1] had proposed the first version of the Doppler hypothesis. According to Terrell the quasars were very nearby objects, they were like stars with the difference that they were ejected by the Galaxy at relativistic speeds. For example, from (2), the speed of a quasar radially ejected would have to be $0.8c$ if its redshift were 2.

Such high speeds are unusual in the context of galactic stars. The kinetic energy required for ejection of a solar mass star with relativistic speeds is of the order of $10^{54} - 10^{55}$ ergs. If most of the quasars seen have been ejected by the Galaxy, the energy requirement may be as high as $\sim 10^{58}$ ergs. With energy of this order coming out of the central part of the Galaxy, we should be able to see other signs of violent activity, e.g., disruption of stellar orbits, generation of hot gas, strong radio emission etc. Contrary to these expectations the Galactic Centre is not seen to be very active.

It was mainly this objection which led F. Hoyle and G.R. Burbidge [2] to suggest a modification of Terrell's idea. Hoyle and Burbidge argued that most of the quasars have been ejected in active galactic nuclei in nearby regions. A typical example of a galactic nucleus with violent activity is shown in figure 5 (see cover). This is the galaxy NGC 5128 which has a cosmological redshift of 0.0016, thus placing it at a distance of ~ 16 million light years (for $H_0^{-1} = 10$ billion years). This galaxy is interesting because it is associated with a strong radio source called Centaurus A. Its nucleus, in common with nuclei of other radio galaxies, shows signs of explosion. The energy generated in a strong radio source may easily exceed $\sim 10^{60}$ ergs. Therefore the energy required for ejection of fast quasars would not prove an embarrassment to such an active galaxy.

In such a theory quasars may be at typical distances of ~ 30 to 300 million light years. That is, the quasars may be 10 to 100 times closer than their distance estimated by the cosmological hypothesis.

What about gravitational redshift? If quasars are highly compact objects, the ratio $2GM/c^2 R$ may be quite large for them. For neutron stars, for example, this ratio may be as high as $1/3$. (Unfortunately, neutron stars do not have visual spectra and so their redshifts could not be measured directly). It is therefore tempting to imagine that quasars are even more compact so that for them $2GM/c^2 R$ approaches unity. For example, to generate a gravitational redshift 2 we need this ratio to be $8/9$ [cf. formula (4)].

There were two difficulties in this approach. First, a detailed examination of the spectra of 3C 273 and 3C 48 by J.L. Greenstein and M. Schmidt [3] showed that to obtain the observed line intensities within the observed line widths, these quasars would have to be extremely massive (about several billion times as massive as the Sun) and would have to be located very close to the Galaxy. This alternative was observationally untenable.

A second, theoretical objection came from the work of H. Bondi [4] who showed that within the reasonable bounds of theoretical physics, no matter what equation of state was used, no massive object in equilibrium could have a surface redshift exceeding 0.62. Thus to explain large redshift quasars esoteric equations of state were needed.

To get round both these difficulties, F. Hoyle and W.A. Fowler [5] suggested that quasars are essentially transparent to light which comes from their deep interior. In the Hoyle-Fowler model, the quasar may be considered as made up of a collection of stars which produce a gravitational potential well at the centre. Gas trapped in the centre radiates light which can emerge through the gaps between the stars with large redshifts (see Figure 6). P.K. Das [6] has considered such models in detail and has shown that redshifts as high as 2 can be obtained this way.

We are now in a position to enter the redshift controversy and outline the arguments for or against the cosmological hypothesis. We will first consider arguments in favour of the cosmological hypothesis and against the non-cosmological alternatives. Next we will describe arguments which pose problems for the cosmological hypothesis and suggest that some alternative to this hypothesis is needed.

V. ARGUMENTS IN FAVOUR OF THE COSMOLOGICAL HYPOTHESIS

Let us first look at an argument **against** the Doppler theory of Hoyle and Burbidge. If quasars are being thrown out from the nucleus of a nearby galaxy, then some of the ejected quasars should be coming towards us. The spectra of such quasars should show blueshifts. In the most recent catalogue of quasars compiled by A. Hewitt and G. Burbidge [7] there are nearly 1600 quasars, **all** of which have redshifts. No blueshifted quasar has yet been seen. Moreover, if the astronomer makes a survey of all quasars in a given region of the sky, which are brighter than a pre-assigned level, then he should find far more blueshifted quasars than redshifted ones. This result, derived by P. Strittmatter in 1967 [cf. [8].] has always been an embarrassment to the Dop-

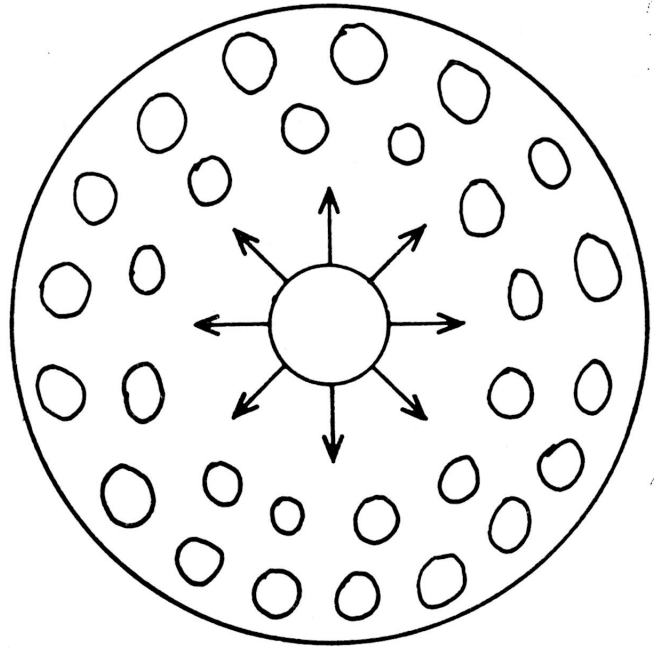


Fig. 6 The Hoyle-Fowler model envisages a collection of stars with a deep gravitational potential well at the centre from where light emerges with high gravitational redshift.

pler theory. In the next section we will return to this point for a possible resolution of the difficulty.

The gravitational redshift model of Hoyle and Fowler also has had a few awkward observations to cope with. The main difficulty is typified by the detailed observations of the quasar 3C 48 which shows a fuzz round the centre [9]. If the fuzz represents the outer periphery of the quasar, then it should show a smaller redshift than the central region (where the gravitational potential well is the deepest). The fuzz, in fact shows slightly higher redshift.

An argument in favour of the cosmological hypothesis puts quasars in a natural sequence following a special class of galaxies called the Seyfert galaxies. The galaxy NGC 1068 shown in Figure 7 is a typical example of Seyfert galaxies. It has a bright nucleus with strong emission lines in its spectrum. Seyfert nuclei and quasars resemble in optical appearance, spectral features and in evidence for internal violent activity. This resemblance has led to the view that quasars are the next step in the evolution of Seyferts wherein the central nucleus completely dominates the outer parts (if any) in visual appearance. Further, if the quasar is very far away, we will see only its nuclear region (which is its brightest part) and this may account for its starlike appearance. Since the redshifts of Seyferts are cosmological so must be the redshifts of quasars.

The spectra of many quasars show absorption lines. With the exception of a few cases, all such quasars seem to have their emission line redshift (z_{em}) greater than their absorption line redshifts (z_{abs}). In fact in quite

a few quasars there are more than one absorption line redshifts. How do these redshifts arise? According to the cosmological hypothesis the absorption lines could arise from absorbing clouds of gas in or around galaxies that lie along the line of sight to the quasar. More than one z_{abs} imply more than one intervening galaxy.

In non-cosmological theories absorption lines would have to arise within the quasar itself, for example, from gas driven outwards by the quasar's own radiation. However, detailed observations of the quasar 3C 286 using 21-cm studies by A. Wolfe suggest that at least in this quasar, the internal velocity differences are so small that the above explanation would not work. It is not clear whether absorption within the quasar is completely ruled out by present observations.

Another approach to establish the cosmological hypothesis makes use of the so called associations between quasars and galaxies. The principle behind this method is as follows. Since quasars are more sparsely distributed across the sky than galaxies, if we find a quasar very close to a galaxy we may conclude that it is physically near the galaxy. To decide what we mean by 'very close', we have to use statistical arguments. Suppose the separation between a quasar Q and a galaxy G is 30 arc second, as shown in Figure 8. A circle centred

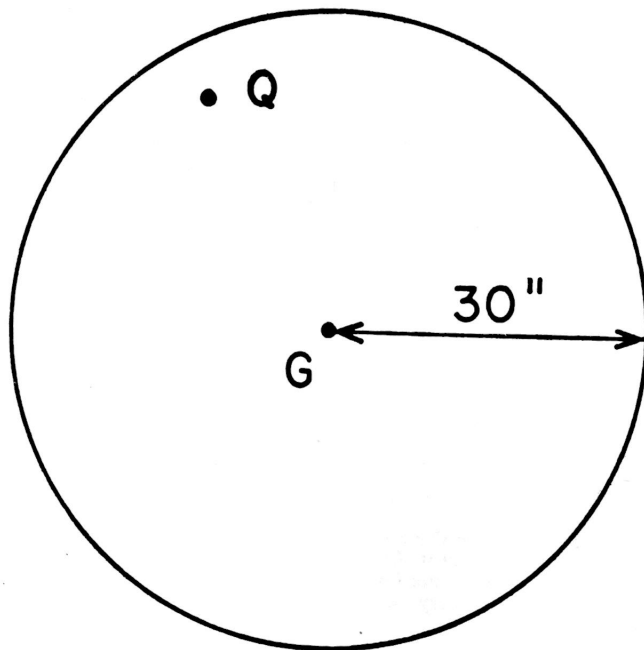


Fig. 8 What is the probability of observing a quasar Q within an angular distance of 30 arc second from the galaxy G?



Fig. 7 The Seyfert galaxy NGC 1068. The lower part of the picture is underexposed to emphasize the central nucleus. (Photograph by courtesy of the Indian Institute of Astrophysics)

on the galaxy and having a radius of 30 arc second would have an angular area of $\pi/4$ square arc minutes, i.e., about 2×10^{-4} square degrees. Suppose further that there are ~ 5 quasars per square degree on the sky which are at least as bright as the quasar in Figure 8. The probability of finding a quasar as bright as, or brighter than, Q within an angular distance of 30 arc second from G is therefore as small as 10^{-3} , if the quasar were **projected by chance** in a direction so near the direction to G.

Assuming that events of such small probability do not happen, the conclusion would be that Q and G have not been projected by chance near each other (see Figure 9) but are actually near each other. In which case, if the cosmological hypothesis is correct, the redshifts of Q and G must be equal. A. Stockton [10] has made controlled searches for such (Q, G) pairs lying within 45 arc second of each other and found in quite a few cases that the redshifts are equal within acceptable limits. Since the redshifts of galaxies are accepted as cosmological in origin, we have reason to draw the same conclusion for quasars. However, in all of Stockton's cases, his selection procedure necessarily had low redshift ($z < 0.45$) quasars.

VI. ARGUMENTS AGAINST THE COSMOLOGICAL HYPOTHESIS.

The ambiguity of interpretation of quasar redshifts would not have existed, had it been possible to measure the distances of quasars from us by some astronomical method. In the absence of any such method it has not been possible, for example, to test the Hubble relation (7) for quasars.

How is the Hubble relation tested for galaxies? For galaxies also, the distance determination is far from

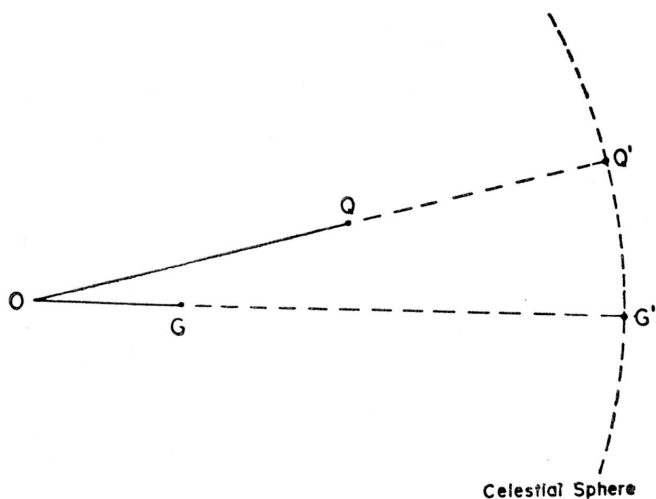


Fig. 9 The observer O sees a quasar Q and galaxy G projected against the sky at Q' , G' . He does not know the radial distances OQ and OG. If the angle QOG is small he deduces that very likely Q and G are near each other, i.e., $OQ \approx OG$.

perfect. Most methods of estimating the distances of galaxies boil down to the use of the inverse square law of illumination. Thus if the rate of emission of energy by a galaxy (called its **luminosity**) is L , then the flux of light received from the galaxy by an observer at a distance D is given by

$$I = L / (4 \pi D^2) \quad (9)$$

The astronomer can measure I and therefore estimate D , if he knows what to assume for L . By restricting himself to a special class of galaxies for whom L does not change much, he has been able to obtain a fairly tight Hubble relation (see Figure 4). If he can repeat this method for quasars he will have shown that the quasar redshifts are cosmological.

Unfortunately this method has not worked. If in Eq(9) L were fixed, then Hubble's law requires that a plot of $\log z$ against $\log I$ be a straight line with slope -2. When such a plot is made for quasars no such relation emerges, the plot is a complete scatter diagram. Although attempts have been made to reduce the scatter by special selection procedures for quasars, the results have been far from convincing. It would be fair to say that had Hubble first observed quasars rather than galaxies, he would not have arrived at his linear law—or indeed at any clear relationship between z and D .

The quasar 3C-9 discovered in 1964 was the first of the high redshift quasars. Its redshift $z \approx 2$ was sufficient to bring the Lyman- α line (whose rest wavelength is $1215 \text{ \AA}$) into the visible part of the spectrum. If the intergalactic medium contained appreciable neutral hydrogen, it would have acted as an efficient absorber of quasar radiation on the blue side of Lyman- α . If the universe were closed, the density of matter would be of the order of $\sim 10^{-5}$ protons per cm^3 . In the early 1960s it was believed that most of this matter would be

in the form of intergalactic neutral hydrogen. If 3C-9 were a very distant object, its continuum radiation on the blue side of Lyman- α should have shown an appreciable dip. No such dip was observed. This negative result can be interpreted two ways: (i) the quasar is local or (ii) the intergalactic medium does not contain neutral hydrogen. To save the cosmological hypothesis its proponents opted for the second alternative.

In the early 1970s, very long baseline interferometry (VLBI) made it possible for the radio astronomers to study the interiors of radio sources at a very small angular resolution, at $\sim$ milli arc seconds. Systematic studies of a few quasars including 3C-273 revealed a very remarkable pattern. The angles subtended by some of the inner regions were increasing far too rapidly. The situation is illustrated in Figure 10 in which we see that the regions A and B subtend an angle θ at the observer

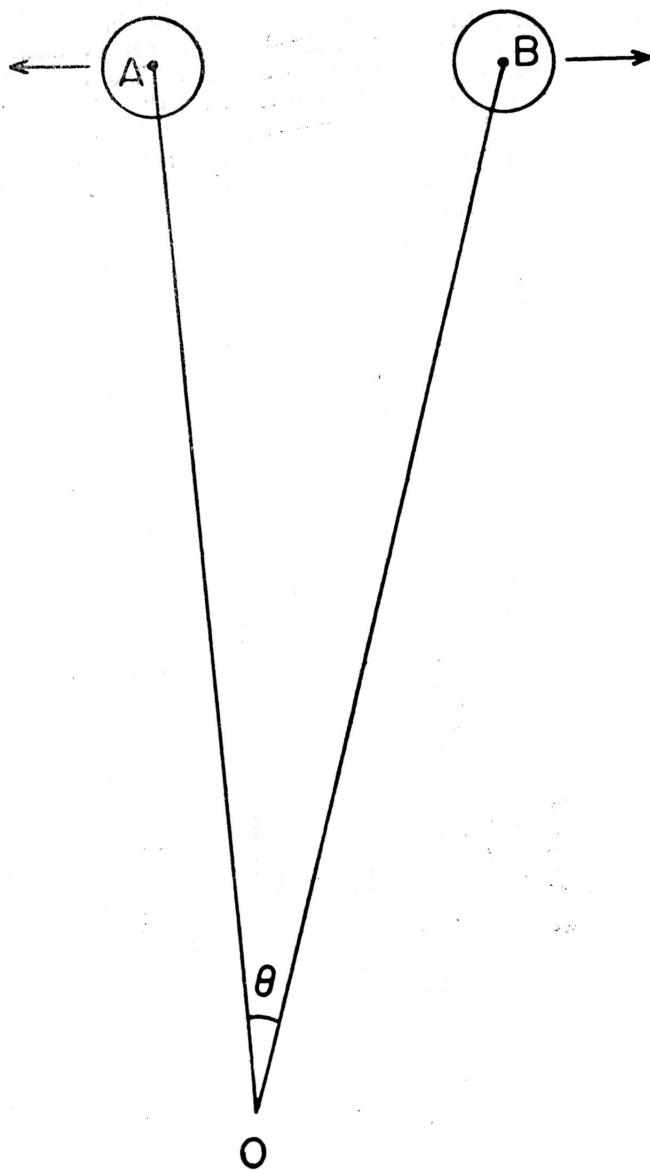


Fig. 10 The line joining the centres of the two blobs A and B subtends an angle θ at the remote observer O. As A and B separate from each other the angle θ increases.

O. If the distance $AB = x$ and the distance of AB from O is D , then we have

$$x = D\theta,$$

$$v = \frac{dx}{dt} = D \frac{d\theta}{dt} \quad (10)$$

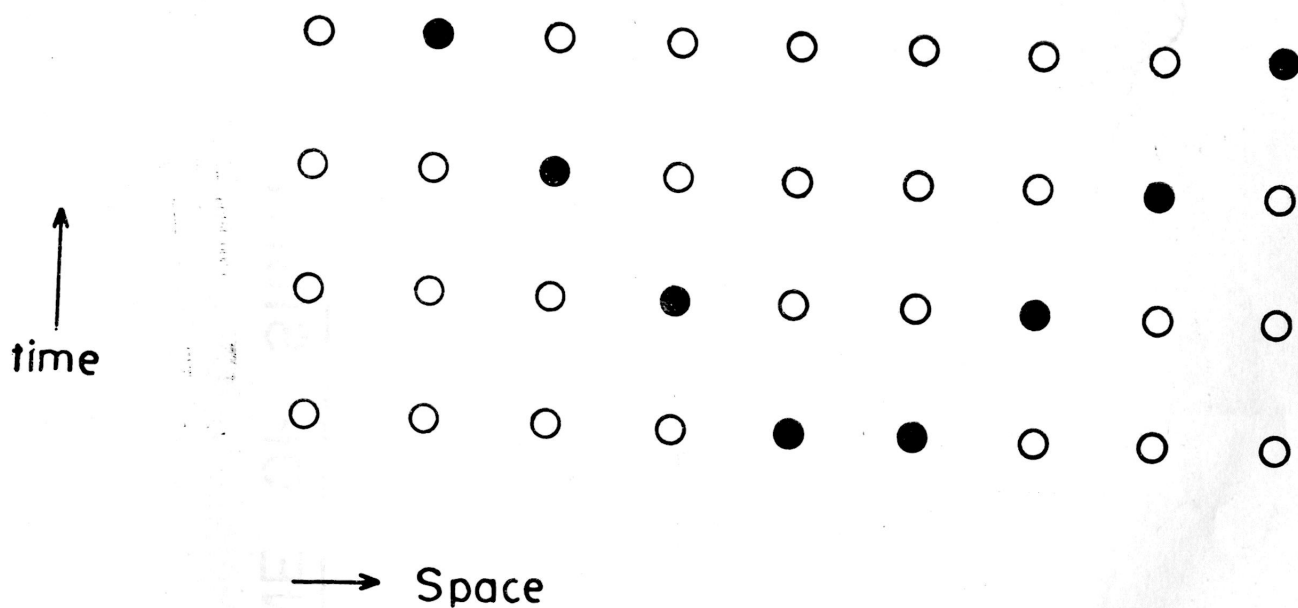
The estimate of v using VLBI exceeds c , the speed of light by a large factor. For example, for 3C-273, $v = 5c$ while for 3C 345, $v = 8c$. Obviously, physics would be in need of serious revision if this conclusion were correct! These superluminal motions can be avoided if D were smaller, i.e., if the quasars were local.

Perhaps this is the correct way of resolving the difficulty. However, even a galaxy 3C-120 shows superluminal motion. Does it mean its distance too is sus-

pect? While the astronomical community may be prepared to accept the breakdown of Hubble's law for quasars, it would be very unwilling to face a similar conclusion for galaxies!

So, to prop up the cosmological hypothesis a third alternative has gained popularity. This alternative suggests that what is 'seen' is not to be taken at face value, that illusions are being created. Three types of illusions are described in Figure 11.

Finally, we describe another attack on the cosmological hypothesis, which has generated considerable controversy. In the previous section we described a statistical method of arguing that a quasar-galaxy pair are physical companions. The main thrust of Stockton's argument was that Q and G near each other have the same redshift. But suppose we find that Q and G are near each other but have different redshifts. This situation was briefly described in Figure 9.



(a)

Fig. 11 In (a) we have the Christmas tree model in which different portions of the source are successively illuminated thus creating the impression that there is a physical movement of the dark blobs.

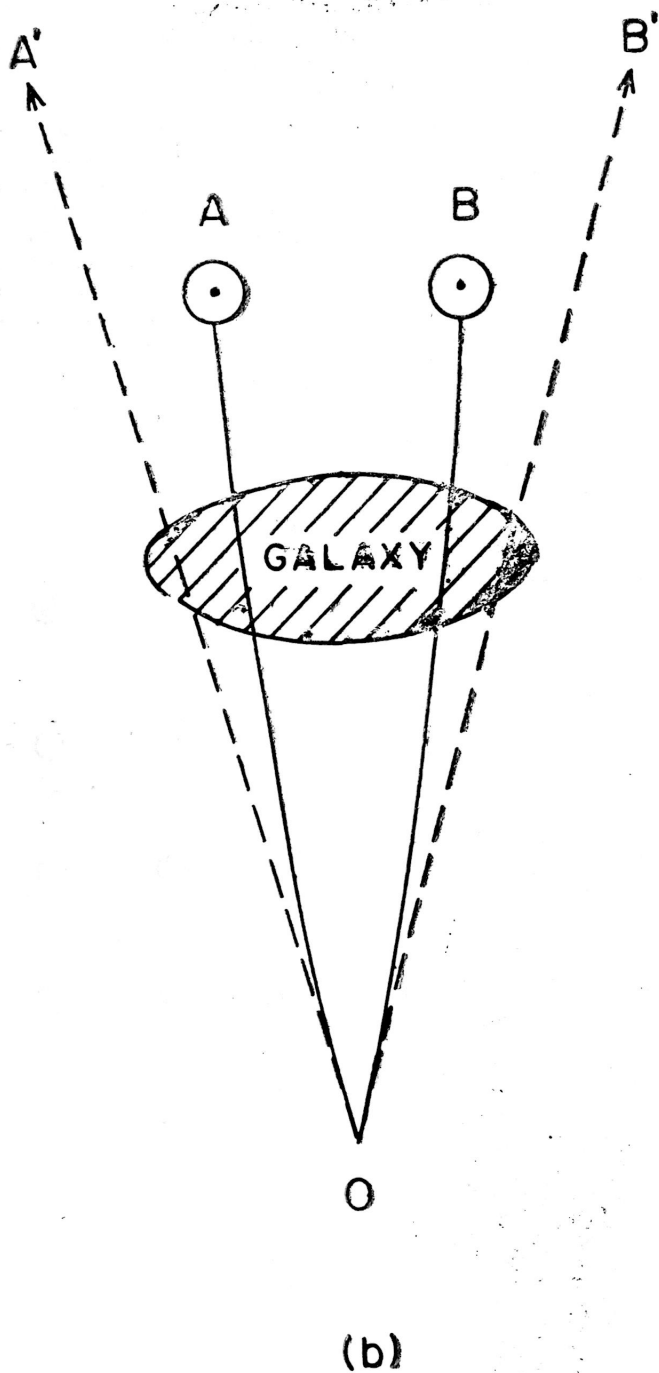


Fig. 11 In (b) an intervening galaxy acts as gravitational screen which bends the rays from the sources. Thus instead of the sources A, B we see the images A', B' moving apart.

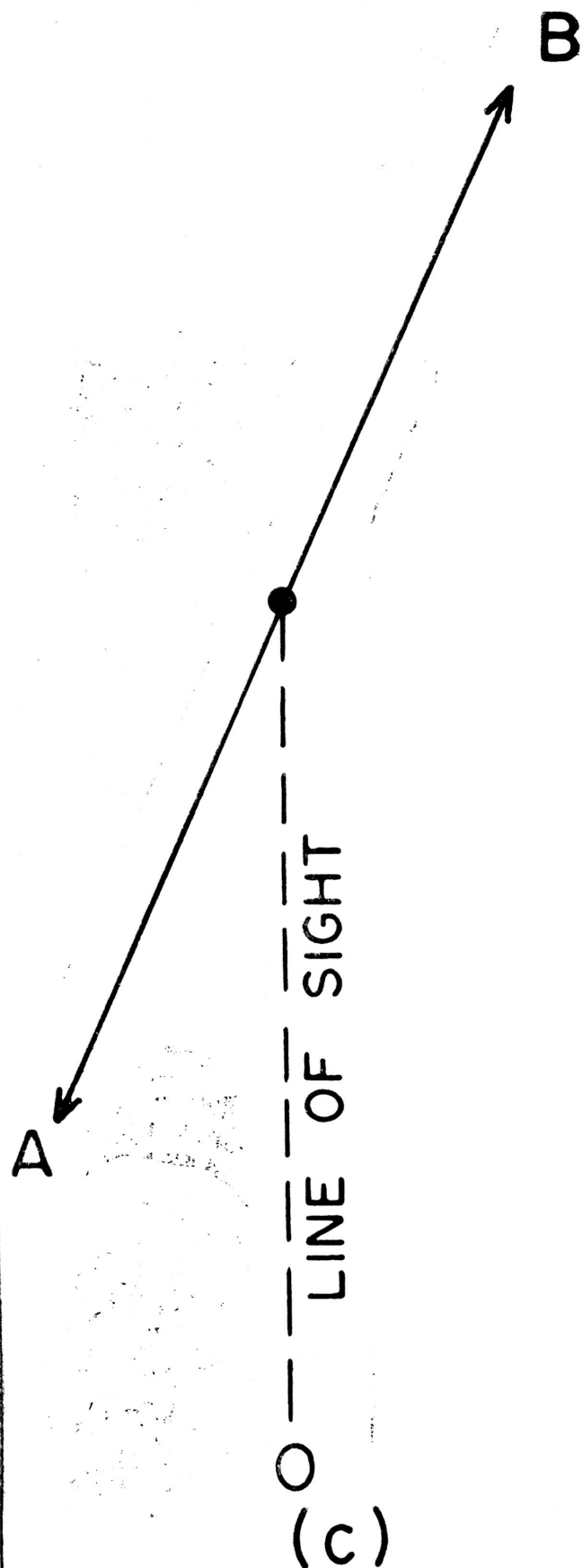


Fig. 11 In (c) it is assumed that A and B separate along a line making a very small angle with the line of sight of O. In this case the projections of A and B appear to move apart at speeds exceeding c . This is currently the most popular explanation.

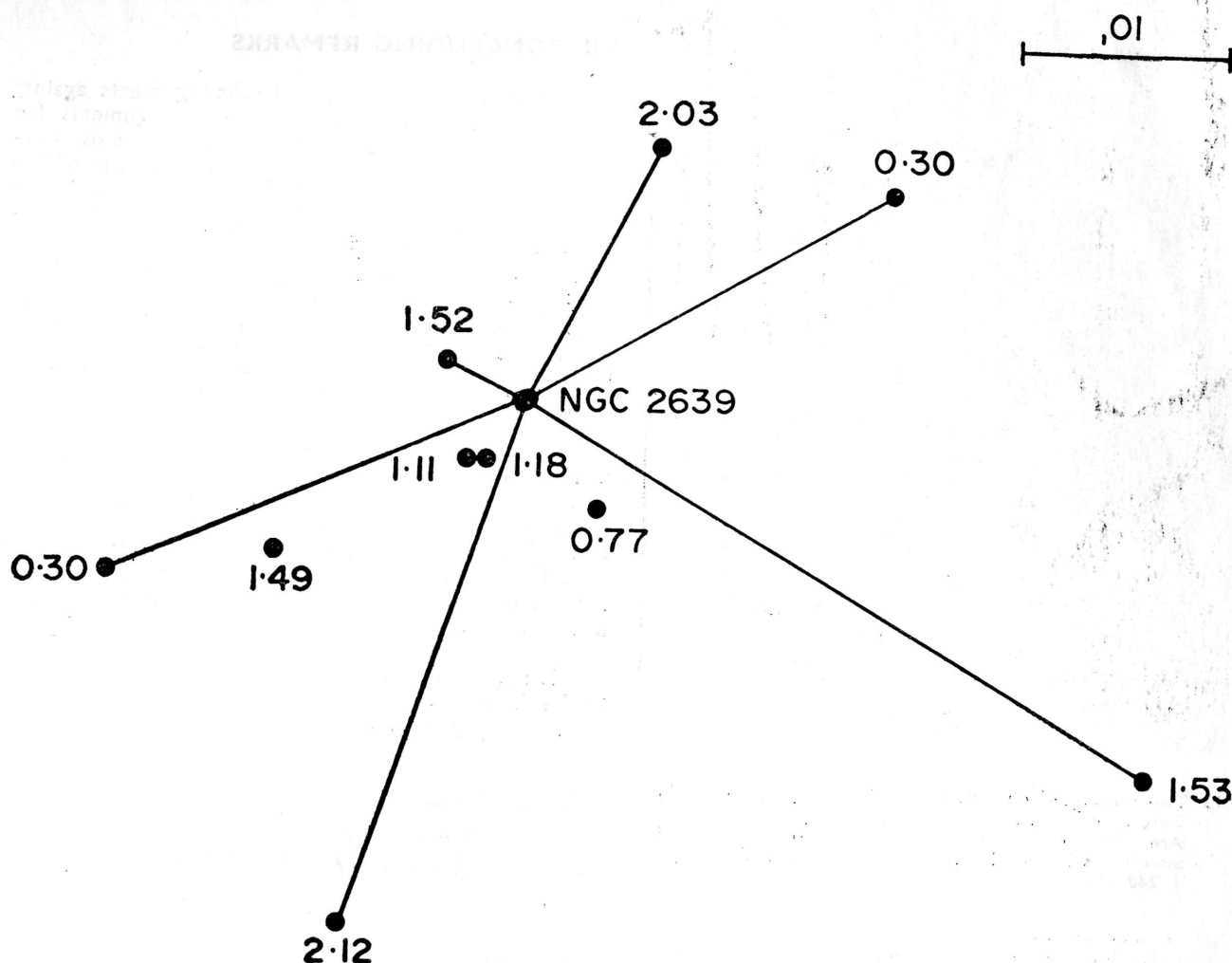


Fig. 12 A group of quasars near the galaxy NGC 2639. The quasar redshifts are given in brackets; the galaxy has a redshift of 0.011. From H. Arp, *Astrophys. J.* **236**, 63 (1980).

H. C. Arp has been discovering many such (Q, G) pairs of discrepant redshifts. Not only this, but in many cases there are mysterious alignments of a number of quasars across a galaxy. Figure 12 describes one of Arp's awkward cases. Are the high redshift quasars grouped round the galaxy associated with it in any way? Were they ejected from the galaxy in a single or in multiple explosions? An even more remarkable arrangement involving quasars only is shown in Figure 13. This arrangement was discovered by Arp and C. Hazard.

Alignments are not unknown to astronomers. Radio sources show blobs of radio emitting regions aligned across a (probable) centre of ejection. Are

quasars also aligned because of some central activity in galactic nuclei? This brings us back to the Doppler theory of Hoyle and Burbidge.

Earlier we had pointed out a serious drawback of the Doppler theory, viz, the expected predominance of blueshifted quasars not seen so far. Recently Hoyle [11] has advanced an explanation as to why no blueshifted quasars are seen. Hoyle's result is briefly described below.

A quasar Q is moving with velocity V relative to an observer O. In the rest frame of the quasar image

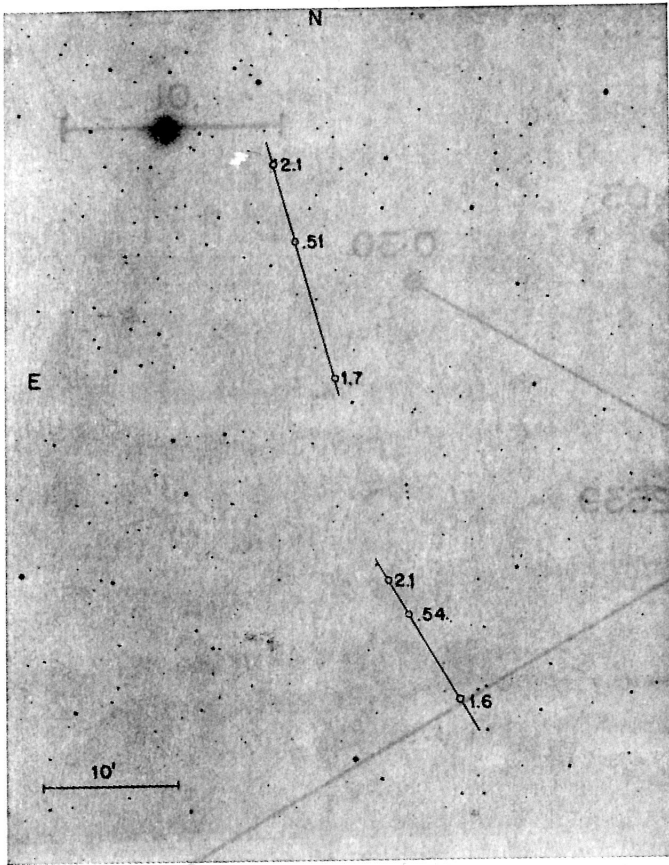


Fig. 13 Two triplets of quasars, each triplet aligned to within 2 arc seconds. The quasar redshifts are given in brackets. Are these chance projection effects or real physical associations? From H. Arp, and C. Hazard, *Astrophys. J.* **240**, 726 (1980).

a cone centred on the backward direction of motion and with a semi-vertical angle θ given by

$$\cos \theta = \frac{c - \sqrt{c^2 - v^2}}{v} \quad (11)$$

For example, $\theta = \pi/3$ for $V = 0.8c$. So long as the quasar emits its radiation within this backward cone, **no observer** at rest relative to O will see the quasar blueshifted.

Thus, to avoid being seen blueshifted a quasar must emit all its radiation within this backward cone, much like an exhaust coming out of a rocket. What physical emission mechanism could lead to such backward emission is not yet known. But, if a satisfactory astrophysical

theory can provide the answer, it will remove the main obstacle to the Doppler theory.

VII. CONCLUDING REMARKS

I have devoted more space to the arguments against the cosmological hypothesis than to the arguments for it because the majority of astronomers (and most physicists) think that the issue is settled in favour of the hypothesis. This is far from the case. If quasars are distant they provide us with useful tools for studying the structure and evolution of the universe. The largest redshift quasar ($z = 3.53$) takes us back to the epoch when the linear size of the universe was about 22% of its present size (assuming that it originated in a big bang). Because of their cosmological importance it is necessary to ensure that quasars are indeed as far away as they are widely believed to be.

As the above discussion shows, considerable doubt and uncertainty surrounds this question. Nor is it clear if the Doppler or gravitational redshift will provide a viable alternative should the cosmological hypothesis fail. If none of the three explanations works, then the physicist must look for a new interpretation for redshift. According to most astronomers that stage has not yet been reached.

It may also be mentioned, by way of caution, that in the three past controversies cited in the Introduction, the minority proved to be right in the end!

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