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Beacons in the Gloom

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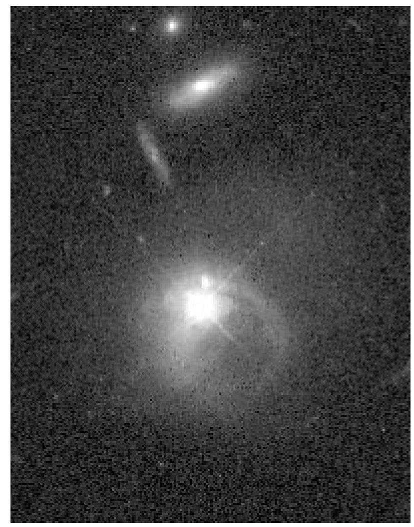


A tussle in the distant Universe. This Hubble Space Telescope image shows evidence for a merger between a quasar and a companion galaxy. The quasar is the bright object just beneath the image center, and the wisps of material around it are remains of a galaxy disrupted by the interaction between it and the quasar. Image courtesy of J. Bahcall (Institute for Advanced Study) and NASA.

Quasars. What lurks behind such a strange name? It took a long time for astronomers to answer this question after these remote objects were actually discovered and named. How the name came about, however, is a much simpler story. Let us begin with this story, as it gives us an insight into the process of discovery in astronomy.

The name quasar is made up with parts of the words "quasi-stellar radio." The origin of the name is closely related to their discovery: Astronomers named this class of objects -- first discovered by their radio emission -- by the way they looked through the optical telescope, that is, like a star.

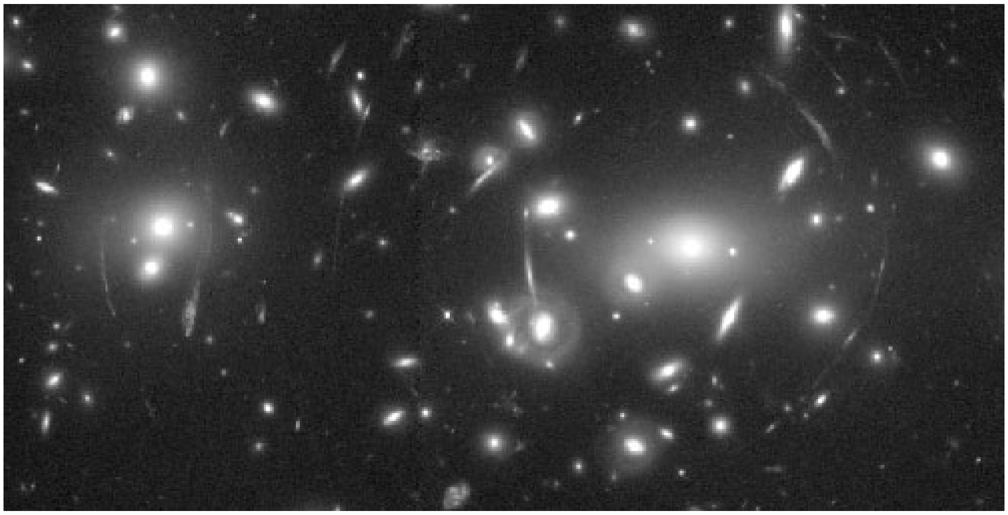
Later, when it was found that most objects of the kind do not show radio emission and are mainly detected in the visible part of the spectrum, they started to be called simply "quasi stellar objects," and the acronym QSO began to be used more frequently. The name quasar remained in use only for those that show radio emission, although this distinction is not followed too strictly, and I will stick with the moniker quasar.

Why were they discovered as radio sources if they can be seen through an optical telescope? The name quasar contains the answer: Since they look like stars in the "visible" sky, and since we see so many stars in the foreground of the Milky Way Galaxy, no matter the direction in which we look, it was unlikely that anybody would check closely what seemed to be just another very faint star. Yet in the radio sky quasars looked quite different from any other object; stars are generally not expected to emit large amounts of radio emission.

A History in the Making

Since the 1920s the idea of an expanding Universe has been supported by Edwin Hubble's discovery that most galaxies or groups of galaxies move away from each other. This is the basis of the Big Bang model of the Universe because it implies that they all may have been very close to each other in the past, if we assume that they moved the same way in the past and in every part of the Universe. This assumption, called the "cosmological principle," is the starting point of our whole knowledge of the Universe as a whole, so it had better be true!

To determine the speed at which distant galaxies are receding from us, astronomers use something called "redshift." As you wait to cross a street, you notice the frequency of the sounds of approaching cars increases, while it decreases quickly as they drive past and away. This effect -- a change in frequency when the source has a component of motion toward or away from you -- was described mathematically by Hans Doppler years ago. What is true for sound is also true for light: The frequency of light received by an observer from a source is lower, and hence "redder," if the source is moving away from the observer. And the greater the source's speed, the larger the "redshift." A "blueshift" would be observed for a source moving toward the observer. Taken together with the notion of an expanding Universe, in which we observe that the most distant objects move the fastest, redshifts provide us with a means to estimate distance: the higher the redshift, the more distant the object.



Lensing on a grand scale. Abell 2218 is the rich galaxy cluster shown in this Hubble Space Telescope image. Because of its great mass, the cluster bends light from distant objects behind it, much as an optical lens bends light, and produces the arc-like structures in the image. Called gravitational lensing, this process brightens, magnifies, and distorts images of those distant objects, which in this case are a population of galaxies that extends from five to ten times the distance to Abell 2218. Image courtesy of W. Couch (University of New South Wales), R. Ellis (Cambridge University), and NASA.

In the 1960s galaxies were known to have redshifts of up to 0.2. Imagine the surprise when in 1963 Maarten Schmidt, an astronomer at Cambridge University, found that what was thought to be an anomalous star with radio emission showed a redshift of 0.158. Such a redshift implied that the "star" was at a great distance, comparable to that of the most distant galaxies known then -- but how could a single star shine with so high a brightness that it could be detected at such a distance? That it was a star had to be ruled out, yet it was still too bright to be identified even as a galaxy.

Other "anomalous star[s] with radio emission" were subsequently discovered to have large redshifts, and although their nature remained unknown for a long time, these powerful objects were recognized immediately by astronomers as the most distant objects in the Universe. Since Schmidt's discovery nearly four decades ago, the race for finding objects at ever higher redshifts has intensified; at present, the record is close to a redshift of 5.

But the eagerness to find distant quasars is not only due to the wish to hold a record. The fact that such bright objects can be observed, and that because of their brightness they can be detected at great distances, has given rise to quasars' use as probes of the furthest regions of the observable Universe: Not only the regions where they actually are, but also those through which their light has traveled before reaching us.

There is a large gap between the most distant galaxies that can be observed and the region where quasars are most abundant. And while there are probably many galaxies in that gap, their light is too faint to reach us, and we can only know of their existence and about their properties through their effects on the light coming from the background quasars. The same applies to galaxies and gas clouds which, although being closer, are too faint to be seen. There are two main ways such galaxies may interact with the light from quasars: They can absorb part of it if they lie directly in the line of sight, or their gravitational force can bend the light rays passing by them.

Beacons in the Gloom

What *are* they?

For us to see them from such great distances, quasars must be producing enormous energy -- they are about 1000 times brighter than an average galaxy! And, to make them even more amazing, the energy originates in a region smaller than a single star! Physicists had not thought about mechanisms to produce such energy from such a small volume until they were confronted with quasars.

One of their choices for the energy source of quasars was a black hole. As matter falls into a black hole, it is squeezed in such a way that the friction between in-falling particles makes the matter hot; light is emitted from this heated material, and the hotter the matter gets, the higher the frequency of light emitted. As analogy, consider what happens at the entrance to a cinema: If movie-goers do not queue properly, a crowd of people forms as all try to pass through the narrow doors. The heat in the crowd rises first due to the proximity of one person to another and second because of the friction between the bodies. On the one hand, it may seem difficult to think that mere friction between bits of matter could account for the energy of a quasar, but, on the other hand, gravity is unimaginably strong near a black hole.

In fact, the black hole solution to the quasar energy problem is the simplest one. Some researchers were somewhat skeptical about black holes altogether (although there is very much indirect evidence for their existence, no black hole has been really seen in a conclusive manner) and tried to find an alternative explanation for quasars. In one such explanation, it was proposed that a large number of supernovae occurring simultaneously over a very long time (as long as a quasar shines) can produce quasars' observed properties. At the present time, it seems that perhaps a combination of both explanations may be acceptable. A black hole in the center could be responsible for producing the frictional energy as well as for triggering a large number of supernovae. Let us now have a closer look at the surroundings of that black hole in the center. How does matter actually rush towards the black hole? The key word to answer this is accretion. It is nothing else than the accumulation of mass onto an object from its surroundings. Like a rolling snowball. But there is something special about astrophysical accretion, something that makes it different from rolling a bigger snowball.

Accretion in outer space tends to take place in a disk-like structure that surrounds the "accreting" object. Does this not remind you of the Solar System? Indeed, the most accepted theory on how the Solar System formed includes the process of accretion of matter onto the dense pocket of matter that eventually formed the Sun. Now you may think that in the case of quasars and their central black holes the same physical process may take place, but scaled up a lot. Well, this is not exactly true: Black holes are very small objects, and, as I said, the energy of a quasar comes from a region which may be smaller than a single star. What is the difference then? It is the density, and, therefore, the gravitational pull due to the black hole which makes the difference - remember, gravity is not related to size, but to mass and density!

The Unified Model for Active Galactic Nuclei

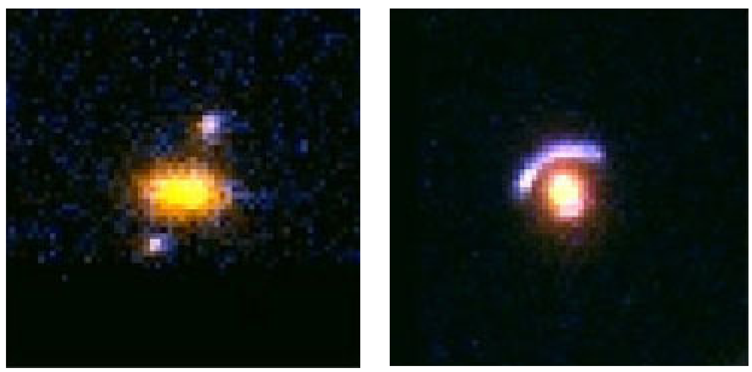
One might ask oneself, does the infalling matter near a black hole not hide the region where the energy forms? How, then, can we see quasars shine so bright? It is true, in fact, that there is matter that hides the quasar's bright center. Before actually getting into the relatively small accretion disk, matter gathers in a large, not-quite-flat "doughnut" of material surrounding the black hole. Thus, depending on one's viewing angle, this torus -- astronomers call it this rather than "doughnut" -- may hide the direct sight of the energy-producing accretion disk.

How does a quasar appear to us if we cannot see the accretion disk surrounding its black hole? The answer to this question is part of what makes the whole issue of quasars very interesting: Throughout the modern astronomical age, we have observed many objects in the Universe that have defied us in our attempts to classify them. The modern quasar model offers a quite natural explanation for these seemingly disparate objects. Striking things like radio galaxies and blazars can be explained as the very same objects as quasars, but being viewed from different angles.

Such an explanatory power makes a theory very attractive to scientists, and they tend to believe such theories as true very quickly - too quickly sometimes! In any case, at the present time, this accreting-black-hole model is accepted as an explanation for the behavior of quasars, radio galaxies, and blazars, known collectively as active galactic nuclei (AGNs), since they are thought to be always in the nucleus of a galaxy. And such galaxies are part of a class known as "active galaxies."

Galactic Nuclei: Old Quasars?

One question remains unanswered by astronomers: Because we see quasars exclusively at great distances -- and, therefore, the light we detect from them comes from a long time ago -- does this mean that all galaxies have had an AGN in their center at some stage, or is it the case that only a few of them did, and only during a short time in the past? Try to build your own theory on this by first obtaining information on the relative numbers of normal galaxies and quasars at high redshift and nearby.



Lenses through the HST. Two examples of gravitational lensing captured by the Hubble Space Telescope: HST 14164+5215 (left) is a pair of faint lensed images on either side of a brighter galaxy, while HST 15433+5352 (right) is a lensed source visible in this image as an extended arc about the elliptical lensing galaxy. Images courtesy of K. Ratnatunga (Carnegie Mellon Univ.) and NASA.

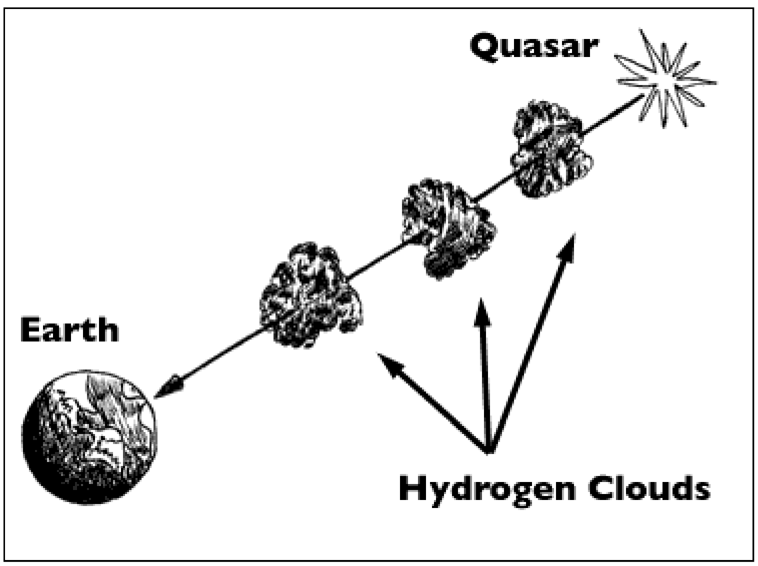
Erik Stengler studied physics in Cologne, Germany, and completed a M.Phil. and a Ph.D. in astronomy at Cambridge University in the United Kingdom. After several years of research in this field, he started a second Ph.D. in science didactics at the University of La Laguna in Spain and recently joined the team in charge of creating the new Interactive Science Museum in San Sebastian, Spain, to be opened in Spring 2000. He can be reached via email at estengler@museosdetenerife.org.

Beacons in the Gloom

Quasars as Probes of the Distant Universe

Absorption of their light by intervening objects

Quasars are ideal objects to use to learn about the distant — and for us practically invisible — Universe. In one situation, we can use light from quasars to probe the material between us and them because that light may pass through one or more galaxies or gas clouds on its way to us. The gas inside the galaxies or the intergalactic clouds acts then as a filter, absorbing selected wavelengths from the quasar light. When the light that ultimately reaches us is analyzed by astronomers, we find distinctive "finger prints" of the gas since each kind of gas absorbs in a different way. These finger prints of the gas appear in quasar spectra as dark lines, places where the light has been taken by the absorbing gas. It’s as easy as that!



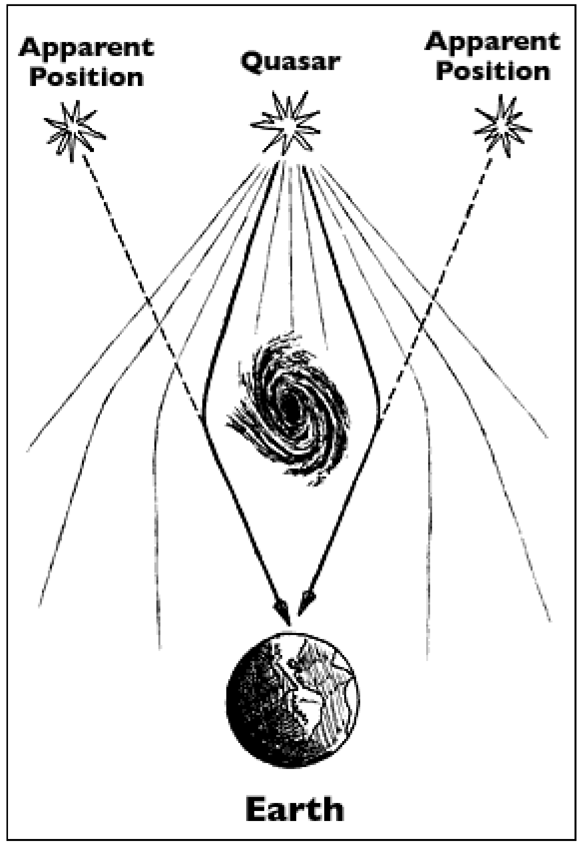
Light from a quasar must pass through clouds of gas and even faint galaxies -- each leaving its imprint on the light -- before we receive it here on Earth. Illustration by James White.

Consider this analogy: When you look at a lamp through a red filter, you see a red lamp because the filter has absorbed all other colors. When analyzing light from quasars, astronomers do exactly the same exercise. The only difference is that a red filter absorbs almost all of the light, letting only the red rays through. Thus, you see red, but you also see the light source quite a lot fainter. The gas in the galaxies, however, absorbs only a small part of the light, letting most of it pass through, and we see quasars shining bright.

But there is more to gain from study of quasar spectra. All of the clouds between the quasar and us have different recessional speeds because of the expansion of the Universe. Now, remember the Doppler effect, and you will understand why the spectral lines caused by absorption of one gas cloud will be shifted from those caused by absorption from a second cloud, and so on. It becomes our job as astronomers to sort out all the clouds between us and the quasar using the clouds' redshifted spectral lines. And knowing the clouds' redshifts enables us to estimate the distances to the clouds.

Gravitational lensing

When the light coming from quasars passes near great concentrations of matter, such as in clusters of galaxies or even individual galaxies, it may be deflected by the gravitational effect of all that matter on the fabric of space. Remember that light can be considered as a beam of particles called photons. Being particles, photons are also subject to the gravitational force. The figure shows how, in such a case, those light rays reaching us from a distant quasar seem to come from different sources which seem to be far apart on the sky. Due to the analogy of this effect to what happens with glass lenses, these instances are called gravitational lensing, and the structures responsible for the lensing, gravitational lenses. In addition, just as glass lenses do, images of gravitationally lensed objects may be amplified. This is why in most cases the direct image of the source is too faint to be seen. In some cases of gravitational lensing, measurement of the strength of the lensing effect permits us to infer how much matter is producing it — matter that is quite often undetectable by other means. Thus, studying cases of gravitational lensing enables us to search for seemingly invisible matter.



Much as an optical lens, a galaxy can bend, distort, and magnify light from objects behind it. If the mass of the intervening galaxy (or cluster of galaxies) is large enough and the geometry of the situation just right, we can detect multiple images of the same object. Illustration by James White.

Classroom Activities

Quasars and the unified model (for middle school ages and up)

Have your students build a cardboard model of the unified model for AGNs. Have them paint the light source yellow, and then place the model — light source, torus, and accretion disk — in the center of the classroom. Now ask them to draw what they see from different angles: from one corner of the classroom, from the top of a desk, etc. After they are finished, you can construct the analogy between their drawn "AGN observations" and the real astronomical observations of different AGNs.

Absorption of quasar light by foreground gas (for high school ages and up)

Place a slide or overhead projector on one side of the classroom and a simple spectrometer on the other. Select five to six students to play the "intervening gas," and give each a monochromatic filter. The other students note which of the gas-cloud students has each filter. While a selected "observer" waits outside the classroom, two or three of the filters are held in the path of the light. Now, the "observer" has to guess who has placed a filter in the line of sight to the light source by checking the spectrum of the light. This procedure is repeated several times with different combinations of filters (and with no filters). The "observers" must draw the observed spectrum and represent it in a simplified intensity-wavelength diagram (colors in place of wavelength and intensity only as a histogram with values of zero or one for no detection and detection, respectively).

THE UNIVERSE IN THE CLASSROOM

Beacons in the Gloom

Gravitational Lensing by a Wine Glass

by Jean Surdej, Université de Liège

The formation of multiple images of a distant quasar by the gravitational lensing effect of a foreground galaxy may be very simply, and faithfully, accounted for by a wine glass experiment.

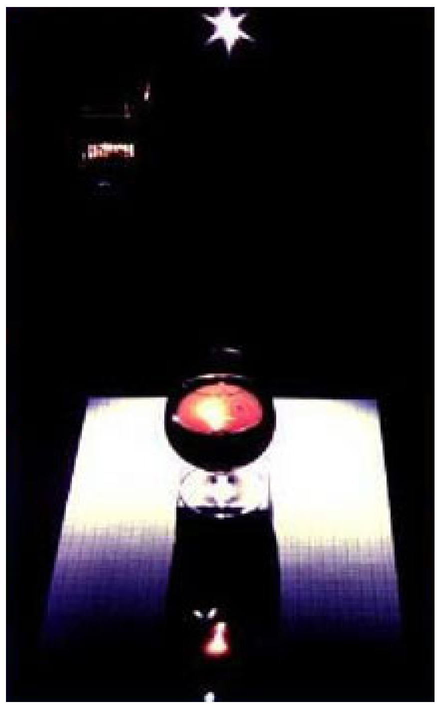


Figure 1. In the wine glass experiment, a bright compact light source (at the top of the photo) serves as a distant quasar. The wine glass on the table distorts the light rays from the "quasar" and produces a caustic having with a triangular shape (see enlargement in Figure 3). Photo courtesy of author.

Use as the quasar light source a candle or a bright compact light source as shown in Figure 1. This source is set at a typical distance of several meters, and somewhat higher, from a table on which a glass of wine is placed. Like a gravitational lens, the wine glass distorts the background field. This space distortion is very well seen through the glass in Figure 2. Because of the presence of the wine glass, the distribution of light on the table is no longer uniform (see Figure 1). Just behind the glass, higher concentrations of light may be seen at some locations in the form of a caustic (i.e., the intersection of a three-dimensional caustic with the plane of the table). The latter is, in the present case, approximately triangular. The three sides and summits of this triangular caustic are named folds and cusps, respectively.

Figure 2. When looking through the wine glass, one sees very conspicuous distortion of the background field -- millimetric paper in this case. Photo courtesy of author.

A blow-up of this caustic is shown in Figure 3. The folds result from the envelope of pairs of tangent light rays from the candle. As a result, an observer setting his or her eye on a fold will see a pair of merging images from the distant quasar. Three merging images will be seen at the location of a cusp.

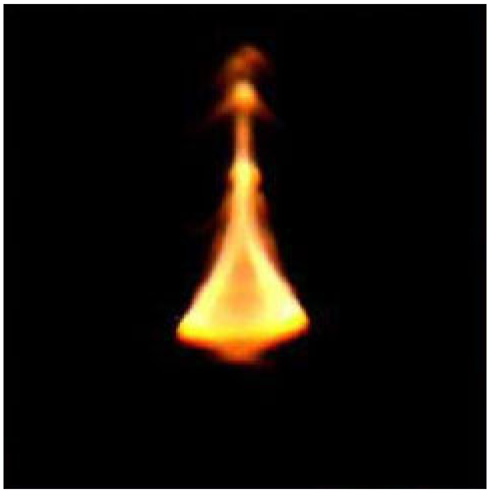


Figure 3. An enlargement of the triangular caustic visible in Figure 1. The caustic results from redistribution by the wine glass of light rays emitted from the "quasar". Photo courtesy of author.

To be able to put your eye at various locations with respect to the caustic, I recommend that you place the glass at the very edge of the table. You may then also observe that the total number of images increases by two when your eye crosses a fold from outside to inside the caustic. Figure 4 shows a photograph made with a camera set up at the caustic's center. As an exercise, draw various diagrams showing the multiple image configurations of the background light source for different positions of your eye with respect to the caustic (folds and cusps) and compare them with the multiple image configurations observed for the known cases of multiply imaged quasars (visit vela.astro.ulg.ac.be/grav_lens/).

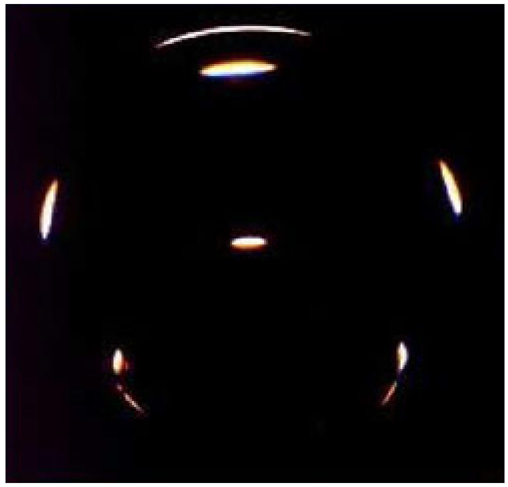


Figure 4. Multipe images of the "quasar" are visible to a camera placed inside the caustic. Photo courtesy of author.

The formation of caustics of light is a generic feature in nature. It arises whenever a foreground object (the wine glass in this experiment, a galaxy acting as a gravitational lens, etc.) distorts the propagation of light rays from a distant light source. For instance, for each pair of quasars and galaxies that exist in the Universe, a more or less complex three dimensional caustic is formed behind each galaxy. Whenever an observer lies close to such a caustic, the former sees multiple images of the distant quasar. Due to the relative motion between the quasar, the lensing galaxy, and the observer, this phenomenon does not last forever. It can be shown that the typical lifetime of a cosmic mirage involving a quasar and a lensing galaxy is of the order of twenty million years.

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