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Variable Galaxies

Large and rapid variations in the light from certain galaxies are being observed.

T. D. Kinman

The largest self-gravitating systems in the universe—containing between 10^8 and 10^{13} stars—are called galaxies. Galaxies usually contain matter in between the stars; this tenuous interstellar medium is mostly hydrogen (neutral or ionized) together with extremely small solid particles whose composition is still uncertain. The ratio of the interstellar to the stellar material varies from place to place within galaxies and from galaxy to galaxy. It is believed that stars form from interstellar material and that they lose some material back to this medium as they evolve. Throughout most of a galaxy the distances between the stars are so great that the stars' motions are governed almost entirely by the gravitational field of the galaxy as a whole. Strong gravitational interactions and possibly collisions between stars are likely only in the very dense nuclei of some galaxies. By comparison the interstellar medium has a much larger cross section for interaction among its components. We may suspect that the wide variety of forms that we observe among galaxies is at least in part a reflection of the extent to which the process of converting interstellar material into stars has progressed.

Most galaxies are composed of stars with surface temperatures of no more than a few ten thousand degrees and of interstellar material in a relatively quiescent state; these galaxies radiate rather little of their energy at radio wavelengths. Exceptions to this rule are the "strong radio galaxies," which have a radio power of the order of 10^{40} to 10^{45} ergs per second. Now the lifetimes of these objects have been estimated by various methods to be in excess of a million years, and since we may suppose that only part of the energy involved in the radiation process is actually observed as radio emission, the total energy involved must be very large indeed. The source of this energy is a very considerable puzzle. Matthews, Morgan, and Schmidt (*1*) showed that these strong radio galaxies were mostly elliptical galaxies of various kinds—some with bright nuclei and extended envelopes (type D), some with brilliant star-like nuclei and less extended envelopes (type N), and some, called "dumbbells," which are related to type D. The strong radio galaxies are also among the intrinsically brightest objects at optical wavelengths that we know (*2*). In the past 5 years we have recognized another type of radio galaxy—the quasi-stellar radio sources. On photographs they are indistinguishable from stars, except that a few show a very faint wisp of attendant nebulosity. The so-called "cosmological interpretation" of the shifts of the lines in the optical spectra of these objects requires that they be at distances such that they must be intrinsically the brightest objects in the universe—10 to 100 times brighter than the strong radio galaxies. Not all astronomers accept this interpretation; some prefer alternative "explanations" of the spectra of these objects which would require that they be at lesser distances and thus intrinsically less bright. Three years ago Sandage (*3*) discovered the quasi-stellar galaxies, which are optically similar to the quasi-stellar radio sources but are not observed to be radio sources or are very weak radio emitters. Such objects can be discovered only through rather laborious observations; it appears, however, that they are much more common than the quasi-stellar radio sources. The relation between the two types of object is as yet unknown. It is not clear at present to what extent there is a sharp physical distinction between the quasi-stellar galaxies and the quasi-stellar radio sources. Evidently the intrinsic radio powers of quasi-stellar objects vary greatly, and the quasi-stellar galaxies may simply be radio sources which are too weak to be detected by radio telescopes now available.

A common property of these intrinsically bright galaxies is their compactness. Measurement of the angular size (let alone the linear size) of a distant galaxy is a difficult matter for the optical astronomer. The angular resolution of our largest optical telescopes is limited by "atmospheric seeing" to little better than 1 second of arc, and the situation is worse for wide-field survey telescopes. Nevertheless, surveys for locating "compact galaxies" have been made by Zwicky (*4*), using the 48-inch (122-centimeter) Schmidt instrument at the Mt. Wilson and Palomar Observatories. Various objects have been found in these surveys, but mostly they have turned out to be relatively nearby objects. Among these are the Seyfert galaxies, which are spiral galaxies with bright compact nuclei. Some are radio sources (although not strong ones), and their nuclei have optical spectra with broad emission lines. This and other similarities between Seyfert galaxies and quasi-stellar objects have suggested to some astronomers that similar physical mechanisms may occur in these galaxies and objects.

The author is an astronomer at the Lick Observatory, University of California, Santa Cruz.

Present attempts to classify galaxies may appear both confusing and confused. Ideally we should use precise physical parameters such as mass, angular momentum, and magnetic field strength. If such parameters are known at all, they are known very imprecisely. Moreover, even the nearest of several of the more interesting types of galaxy are so remote that we can obtain virtually no knowledge of their structure directly from observation at optical wavelengths. A few years ago astronomers thought that every galaxy would always appear the same to us except for the minor perturbations caused by the presence of variable stars or an occasional supernova outburst. We have recently found that the light from certain of the galaxies mentioned above does change, not only by large amounts but in surprisingly short periods of time. These remarkable variable galaxies may well be passing through one of the most active phases of their evolution.

Although all these objects are designated here as "galaxies," only certain types (for example, the Seyfert galaxies) show evidence that they contain stars and so merit this designation. There are, however, enough similarities between those objects which have a stellar component and those which do not to warrant the inclusion of all under some generic title. The word *galaxy* is used in the very broad sense to cover objects which are outside our own galaxy (and unlike any objects within it) and which show some similarities in their properties.

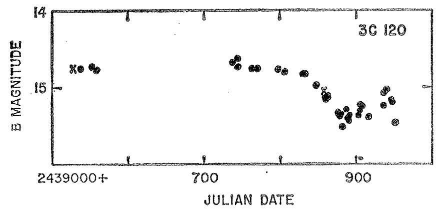

Fig. 1. The brightness variations of the nucleus of the Seyfert galaxy 3C 120 (see *22*). (Solid circles) Lick photographic observations; (crosses) photoelectric observations.

Discovery of Variable Galaxies

Source 3C 48 was the first quasi-stellar radio source which was identified with an optical object. Following this identification, Smith and Hoffleit (*5*) examined old plates in the Harvard collection for evidence of past variability. They found none—probably because the faintness of the object and the quality of the plates were such that only rather large changes could have been detected. Later, Matthews and Sandage (*6*) used a photoelectric photometer to show that 3C 48 varied by 0.4 magnitude (*7*) in just over a year. Sandage has since discovered, by this means, several more quasi-stellar radio sources that are optical variables.

When 3C 273 was identified, Smith (*8*) examined many old Harvard plates and found that its brightness has varied by a factor of 2 in the past 20 years. Similar variations were found by Sharov and Efremov (*9*) from old plates in the Pulkovo Observatory (U.S.S.R.) collection. The variations occurred over periods of the order of 10 years; there were also brief "flashes" with a duration of months or even weeks.

Variability at radio wavelengths was first discovered by Dent (*10*) in 1965 for the sources 3C 273, 3C 279, and 3C 345. Sholomitsky's (*11*) earlier discovery of rapid variations in CTA 102 has not been confirmed. Many radio variables have since been discovered; as a rough rule, radio variables are also optical variables. The radio variations are not discussed here in any detail, but I might note that they have been detected at wavelengths shorter than about 40 centimeters and that the amplitude and rapidity of these variations increases with decreasing wavelength. Low (*12*) has also shown that variations occur at various wavelengths in the infrared.

In 1967, Fitch, Pacholczyk, and Weymann (*13*) discovered photoelectrically that variations were occurring in the nucleus of the Seyfert galaxy NGC 4151. These astronomers are engaged in a continuing program at the Steward Observatory (University of Arizona) to study these variations. Earlier this year I showed photographically that the nucleus of another Seyfert galaxy (3C 120) had decreased in brightness by a factor of about 2 in 50 days (*14*) (Fig. 1). Penston has since pointed out that 3C 120 was discovered as early as 1940, by Hanley and Shapley (*15*), and thought to be an irregular variable star. Apparently the extended parts of this galaxy were not seen on the early photographs.

Also, in 1967, Oke (*16*) and Sandage discovered photoelectrically that the N-type galaxy 3C 371 was optically variable. A subsequent reexamination of old Harvard plates by Usher and Manley (*17*) showed that its brightness had varied by a factor of 4 over the past 70 years. Recently Sandage (*18*) has found that three other galaxies of this type are variable, while Oke, Sargent, Neugebauer, and Beklin (*19*) have found that one of Zwicky's compact galaxies varied by half a magnitude in 50 days. The occurrence of variability is therefore well established in several types of galaxies. Of these the only ones which are close enough for us to observe their structure in any detail at optical wavelengths are the Seyfert galaxies, in which it is the compact bright nucleus that varies and not the extended spiral galaxy of stars and interstellar medium. Even in these objects the variable nucleus is so small that it is probably not resolved by the largest telescopes.

Programs for Observing Variable Galaxies

The modern photoelectric detector affords the best means of making accurate determinations of the optical brightness of an astronomical object. Most of the discoveries noted above were made with photoelectric instruments, which can measure a small change in brightness or small changes in the spectral energy distribution of these galaxies. Generally speaking, however, photoelectric instruments sufficiently complex for observing faint objects are to be found only on large telescopes, on which observing time is limited. Also, the photoelectric method can be used profitably only on nights when the sky is uniformly transparent. In order to observe at very frequent intervals, therefore, one has to fall back on the photographic method. In that method a photograph is taken of the object, and the photographic image is compared with the images of stars in the same field by means of an instrument called an astrophotometer. The brightnesses of the comparison stars may be determined photoelectrically, so that one is essentially using the photographic plate as a means of interpolation. Suitable photographs can be taken with a modest-size telescope (aperture 20 inches or even less); the root-mean-square precision of a single observation is about 0.06 or 0.07 magnitude for an object of 17th magnitude. The photographic method is suited to making frequent observations of a few objects even if the telescope has a long focal ratio and is therefore slow. A program of this type is in progress at the Lick Observatory. If a fast telescope is available, so that exposure times are short, a larger number of objects may be monitored. A program of this type is understood to be in progress at the Mt. Wilson and Palomar Observatories, with the very fast 48-inch Schmidt telescope. Another program of the same general type is being carried on by Cannon and Penston at the Royal Greenwich Observatory in England, and another, by Barbieri and Abati-Erculiani at the Asiago Observatory in Italy.

For investigating variations which may have occurred in the past, the only recourse is examination of collections of old photographic plates, such as the collection at Harvard. Work of this kind is currently being done by Angione of the Astronomy Department of the University of Texas. Little of this work is published yet, since it will take time—perhaps several years in some cases—for the programs to be completed. Results of the sort that may be expected are therefore illustrated here by discussion of some of the work to which I have contributed at the Lick Observatory (*20*). This work has been done largely with the 20-inch Astrograph (a refractor) and, to a lesser extent, with the Crossley 36-inch reflector. These telescopes have been used with blue-sensitive plates to obtain magnitudes which refer to the blue part of the spectrum (B magnitudes). The photoelectric calibration of the comparison stars was performed with the 120-inch reflector. In recent months a program involving the use of yellow-sensitive plates and a refractor of 12-inch aperture has been started for studying some of the brighter objects, but it is too early to report on these observations.

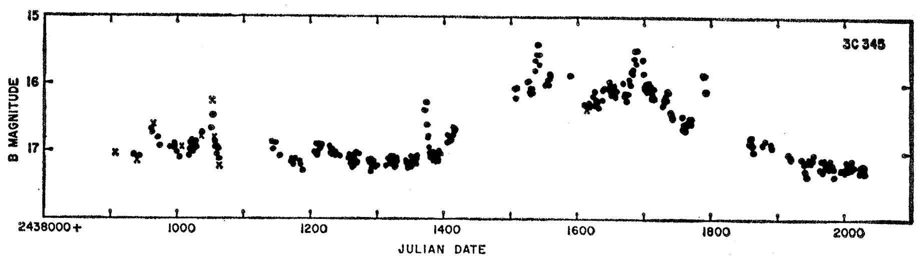

Fig. 2. The brightness variations of the quasi-stellar source 3C 345. (Solid circles) Lick photographic observations; (crosses) photoelectric observations by Wampler, by Sandage, and by Kinman.

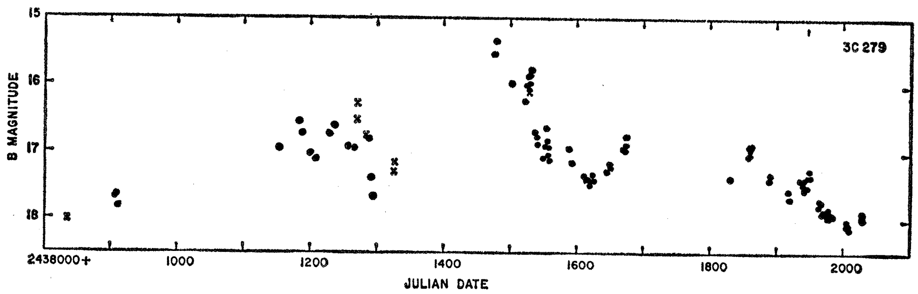

Fig. 3. The brightness variations of the quasi-stellar source 3C 279. (Solid circles) Lick photographic observations; (crosses) various photoelectric observations by Oke and by Kinman.

Light Curves of Some Variable Galaxies

3C 345. Object 3C 345 was discovered to be an optical variable by Goldsmith and Kinman (*21*), and it has since been monitored intensively. The light curve is shown in Fig. 2; gaps in observations occur every year for a few months, when the object is too near the sun for nighttime observation, and also every month for about 10 days around full moon, when the sky is too bright for photography. Time (the abscissa in Fig. 2) is measured in Julian Days (JD) (*22*). The light curve is characterized by two features: short outbursts of little more than 10 to 20 days' duration and a fairly steady rise and fall in brightness over a period of several hundred days. The observations prior to JD 2439800 were recently analyzed (*23*), and seven outbursts of short duration were identified; all but one of these involved a brightening by a factor of at least 2. These outbursts seem to repeat after intervals of about 80 days, and the analysis indicates that there is only one chance in several hundred that this repetition could occur by chance. There is a smaller probability that a 320-day periodicity is also present. The 80-day periodicity is clearly very far from perfect; the outbursts do not all have the same duration and amplitude, and, on one occasion (~ JD 2439610), the object was abnormally faint when an outburst might reasonably have been expected. One may argue that this behavior could be expected if 3C 345 is rotating and the outbursts are caused by the transit of directionally radiating active areas across its face. The more slowly varying component could be due to a more extended region of emission. Photoelectric observations made with the 120-inch reflector during 1967 showed that the light from 3C 345 had a high and variable polarization, and analysis shows that the radiation from 3C 345 may be considered to have three components: (A) an unpolarized component of brightness equal to that of the object at minimum light; (B) the component responsible for the slow variation, which was about 17 percent polarized; and (C) the component responsible for the short-duration outbursts, which had a high but undetermined amount of polarization.

Subsequent observations have shown that the slowly varying component (B) has gradually declined in brightness and is no longer present. Furthermore, there have been no more short-duration outbursts, although two might have been expected on the basis of an 80-day periodicity. Clearly this lack of outbursts has not helped to establish the previous conclusion that the outbursts are periodic and excludes the possibility that they are a permanent feature of the light curve. The disappearance of the outbursts is, however, quite compatible with the theory that they are caused by some temporary phenomenon on the surface of a rotating object.

3C 279. The light curve of quasi-stellar radio source 3C 279 (Fig. 3) is less complete than the curve for 3C 345 although it covers a similar interval of time. The range of brightness (nearly 3 magnitudes, or brightness extremes differing by a factor of 16) is rivaled by only one other object so far discovered: 3C 446. The general characteristics of the light curve are similar to those of the curve for 3C 345 in that there is a

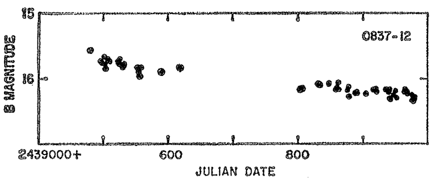

Fig. 4. The brightness variations of the quasi-stellar source PKS 0837-12. (Solid circle at far left) The discovery plate (see text); (other solid circles) Lick photographic observations.

combination of short-duration outbursts and longer-period variations. A very rapid change amounting to 0.25 magnitude in a single day was observed by Oke (*24*) with a photoelectric scanner in 1966. Polarization measurements by me and also by Elvius (*25*) showed that the light from this object was highly polarized in 1967.

3C 446. In June 1966, Sandage (*26*) discovered that quasi-stellar radio source 3C 446 had a B magnitude of 15.7, corresponding to an increase in brightness by a factor of 17 from the value obtained 8 months earlier. Subsequent photographic photometry at Lick, Yale, and Herstmonceux observatories showed a most complicated set of light variations (with a factor-of-3 range) during the remainder of that year. Sandage and his colleagues showed that the brightness change occurred in the continuum rather than in the emission lines. This was also the first object in which a large time-dependent polarization was discovered (*27*). The object has been monitored as often as possible since this outburst, and in 1967 it showed a decline to its former brightness, followed by another, but smaller, brightening. This year it is still fairly faint but still variable. The light curve is much more complex than that for 3C 345. It may be that these relationships indicate a general rule—the greater the amplitude of the variation, the more complex the variation.

PKS 0837-12. Quasi-stellar radio source PKS 0837-12 was identified by Bolton from a plate obtained with the Schmidt telescope at Palomar in December 1967. It was noted at this time that this source was considerably brighter than it appears to be in the *Palomar Sky Survey Atlas.* The Lick observations (Fig. 4) show that a fairly steady decline in brightness has occurred since then, and there is no evidence of short-duration outbursts. In 1967 this object appeared not to have any polarization greater than about 2 percent; in general character the light curve is reminiscent of the latest observations of 3C 345.

3C 351. The light curve of quasi-stellar radio source 3C 351 (Fig. 5) is less complete than the curves for the other objects listed, and, of all the objects discovered photographically, 3C 351 is the one whose light curve has the smallest amplitude. The variability was discovered by Cannon and Penston (*28*), and their observations are included in Fig. 5. A zero point correction was added to Cannon and Penston's observations for correspondence with the photometric system of the Lick observations; otherwise the two sets of photographic observations agree well.

3C 120. Unlike the other objects listed here, 3C 120 is a Seyfert galaxy. It was cataloged as a compact galaxy by both Zwicky and Vorontov-Velyaminov and Arhipova and appears in several radio source catalogs. As mentioned above, its variability was known as early as 1940. Pauliny-Toth and Kellerman (*29*) have found that the rapid radio variations observed compare well with those that would be expected from a homogeneous cloud of relativistic electrons and magnetic field expanding at a constant rate. They deduce upper limits of 0.6 of the velocity of light for the velocity of expansion when the apparent age of the expansion is 0.7 year. The optical variability was rediscovered this year (*14*); the light curve is shown in Fig. 1. The magnitudes are probably somewhat less accurate than those obtained for the other objects (because of the extended nature of 3C 120), but the rapid decline, by a factor of about 2, is well shown. Unfortunately the times (deduced by Pauliny-Toth and Kellerman) when the expanding clouds started their expansion are not covered by these optical observations, so we do not yet know if there are significant optical changes at these instants. It is hoped that future observations may reveal whether or not this is the case. No optical polarization has been observed in 3C 120 as yet. It probably has about the same intrinsic optical brightness as our own galaxy, whereas the brightness of the quasi-stellar radio sources described here may well be greater by several orders of magnitude.

Table 1. The red shift (z) and the actual time interval (t_0) in the rest frame* of the object, corresponding to an observed time interval of 1 day.

Object	z	t_0 (days)
3C 120	0.033	0.968
PKS 0837-12	.200	.833
3C 351	.371	.729
3C 279	.538	.650
3C 345	.595	.627
3C 446	1.403	.416

* The rest frame is a frame of reference which is at rest with respect to the object.

The time scales given above are those measured by the observer; to obtain time scales at the object we must divide by $(1 + z)$, where z is the red shift of the object (*30*). Table 1 gives the appropriate conversion data; it may be seen that, in the reference system of the object itself, the variations are significantly faster than they are when we actually observe them.

It may well be that all the quasi-stellar objects, N-type galaxies, and Seyfert galaxies are to some extent variable. We do not know whether the most violent changes are characteristic of only certain specific types or whether these changes occur at certain times for all these variable galaxies. Generalizations based on such a small number of data are bound to be exceedingly risky. Nevertheless we may hazard some conclusions, while realizing that they may well be premature.

1) Many of these objects show a small amount of optical polarization, but large polarizations (>5 percent) seem to occur only in objects showing large-amplitude variations.

2) The variations of the quasi-stellar sources seem not to be fluctuations in brightness about a mean value; rather they appear to be temporary increases in brightness above some minimum

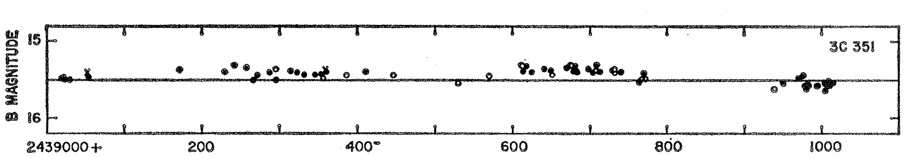

Fig. 5. The brightness variations of the quasi-stellar source 3C 351. (Solid circles) Lick photographic observations; (open circles) Herstmonceux photographic observations; (crosses) photoelectric observations by Sandage and by Kinman.

value, so the term *outburst* seems justified. It is not at all certain that this is true of the other types of object, such as Seyfert galaxies.

3) Unlike most kinds of intrinsic variations observed in stars, in which the brightening generally occurs more rapidly than the fading, brightening and fading in these objects are equally rapid.

4) The complexity of the light curves appears to increase as the amplitude of the variations increases.

5) The continuous optical radiation from the quasi-stellar objects tends to be redder when the objects are brighter, but there is probably no simple relationship between color and brightness. This is scarcely surprising if the radiation that we observe has several components.

6) Generally the same objects show both radio and optical variations. No relationship has yet been determined between the variations in the two parts of the spectrum, however. It is likely that the two types of radiation come from quite different regions of the object, and so no very close relationship should be expected.

Interpretation of the Variations

Most of the processes that have been suggested to account for the rapid release of large amounts of energy in these galaxies (for example, stellar collisions, supernovae explosions) would be expected to produce quite random variations in the output of light. Any periodic behavior would be hard to understand if such mechanisms were operating, whereas periodic behavior would be understandable if we were dealing with a rotating or pulsating body. It therefore seems worth while to continue the search for periodicities, so that the existence of periodic phenomena can be properly established or discounted. Any satisfactory theory must account not only for the variations of relatively large amplitude that are observed in some of these objects but also for the near-constancy of the light output in others; these differences might be due to differences in the aspect of observation as well as to actual secular changes. The high degree of polarization that is observed in the most violent variables indicates that there is a considerable degree of order in the mechanism involved in producing an outburst. The lower degree of polarization observed in quiescent objects shows that the "aligning" or ordering processes are less effective in these objects.

The angular momentum per unit mass of most of the material we observe in nearby galaxies is such that, if compact galaxies were formed from the same material, they would have to lose a great deal of angular momentum in order to achieve any kind of stability. We may therefore argue that, if the material is confined to a small region, it is likely to be in rapid rotation.

It is sometimes assumed that, if a significant variation in a time interval ΔT is observed, then the dimensions of the emitting part of the object cannot be much larger than the product of ΔT and the velocity of light. This would limit the dimensions of the part of the galaxy producing the variations to less than 1 light-day. If the radiation is being emitted by the synchrotron mechanism by relativistic electrons spiraling in a magnetic field, there are severe theoretical difficulties because of the high energy density implied by this small size. However, Rees and Simon (*31*) have pointed out that the diameter can be considerably larger (and the energy density therefore can be much reduced) if the velocity of the medium emitting the radiation approaches that of light. Velocities as great as $0.6c$ are implied by the analysis of the radio variations of 3C 120 by Pauliny-Toth and Kellerman. It seems likely that the variable optical radiation is produced by extremely high energy electrons emitting synchrotron radiation; this type of radiation can be highly polarized, and this polarization indicates a high degree of order in the trajectories of the electrons.

A very different explanation of the variability of 3C 446 was put forward by Cannon and Penston (*32*) and also by McCrea (*33*). They suggested that the variations were produced by occultation of the source by opaque clouds. Difficulties in accepting this mechanism have been pointed out by Burbidge (*34*), but it might be appropriate as a subsidiary means of explaining long-term variations, particularly in objects such as Seyfert galaxies.

To some the variability of these galaxies may seem to be a nuisance which disguises from us, as it were, the equilibrium state of these objects. I believe the true situation to be quite the reverse: if these galaxies emitted their radiation steadily, we should have far less information with which to investigate them. The variations help us to see something like an experiment in progress—one which can perhaps show us how the energy is released and how it is transmitted to us through the outer parts of these galaxies. The definition of a galaxy with which this article began may make the term seem inapplicable to some of the objects discussed, but more precise terminology will come only with a better understanding of the nature of these objects. One thing is certain: the discoveries of the past few years have disclosed a most interesting field of research which will occupy astronomers for many years to come.

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