Reports

Quasars Revisited: Rapid Time Variations Observed Via Very-Long-Baseline Interferometry

Abstract. *Recent Goldstone-Haystack radio interferometric observations of the quasars 3C 279 and 3C 273 reveal rapid variations in their fine structure. Most notably, the data for 3C 279, interpreted in terms of a symmetric double-source model and the accepted red-shift distance, indicate differential proper motion corresponding to an apparent speed about ten times that of light. A number of possible mechanisms that might give rise to such an apparent speed are considered; although several may be plausible, no definitive choice can be made on the basis of present evidence. More interferometric observations of quasars are clearly needed to clarify their structure and internal kinematics.*

New discoveries about quasars deepen the agony as well as the joy of the theoretical astrophysicist. In a previous report (*1*), we described the surprising fine structure exhibited by the quasars 3C 279 and 3C 273 when studied in October 1970 with the Goldstone-Haystack radio interferometer. These observations were repeated in February 1971 at the same 7840-Mhz radio frequency and have disclosed remarkably rapid and difficult-to-understand changes in the apparent structure of both quasars.

Observations of 3C 279 were made on 14 and 26 February 1971 and on each day extended over nearly the entire period of mutual visibility at both antenna sites (*2*). Data for 3C 273 were obtained on only the first of these two days. The resultant patterns of the fringe amplitudes are shown in Figs. 1 and 2 and compared there with the similar data obtained in October 1970 (*3*). The new data exhibit somewhat smaller fluctuations primarily because in February, as contrasted with October, the ray paths from the sources to the observer pass far from the solar corona. In this report we concentrate on 3C 279 because the interpretations so far suggested for its structure all seem startling. More data are required before reasonable speculations can be put forward with regard to the structure of 3C 273.

The most striking aspect of the 3C 279 fringe-amplitude curves (Fig. 1) is the change by about 45 minutes in the time of occurrence of each of the nulls (*4*). Moreover, the data from 26 February appear to show a further displacement of the second null by about 4 to 5 minutes relative to the position of that null 12 days earlier (*5*). Although the relative error is large, the rate of movement of the second null, as determined from the observations in February, seems to agree with the October–February rate.

What models of the brightness distribution of 3C 279 are consistent with these fringe-amplitude patterns? Following William of Ockham, we have so far investigated in detail only simple models that yield consistency: symmetric double sources in which the radiation from different spatial locations is incoherent. We assume symmetry because the depths of the nulls in the fringe-amplitude curves indicate that the contributions to the correlated flux from each half of a double source are equal to within a few percent (*6*). A two-point-source model, the simplest of this class, matches the October observations quite well (*1*) but yields uncomfortably large residuals when applied to the February data. A symmetric double-source model with extended components, on the other hand, gives good agreement with the combined data set (*7*). A number of different models of this latter type were considered. For illustration we show in Fig. 3 the residuals from a least-squares solution for a typical configuration in which each of the two components was represented by the same circularly symmetric brightness distribution with the intensity falling off from the center in a gaussian fashion. The separation between the two components and their (linear) rates of change were estimated independently in right ascension and declination. The radius of the brightness distribution for each component was estimated, but was not allowed to vary with time. To test consistency, that fraction of the total flux from 3C 279 accounted for by the model was estimated independently from the data for each of the 4 days shown in Fig. 1. This nine-parameter solution yielded values of about 0.5 for this fraction with the total spread from the 4 days being only about 0.1. The

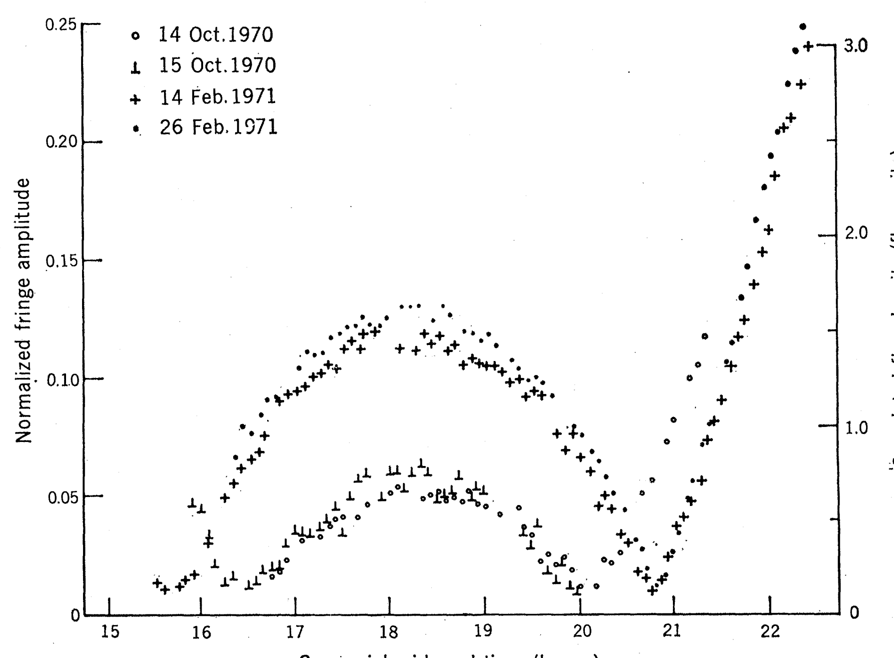

Fig. 1. Fringe-amplitude data from observations of 3C 279 with the Goldstone-Haystack interferometer. Each point is based on 110 seconds of integration.

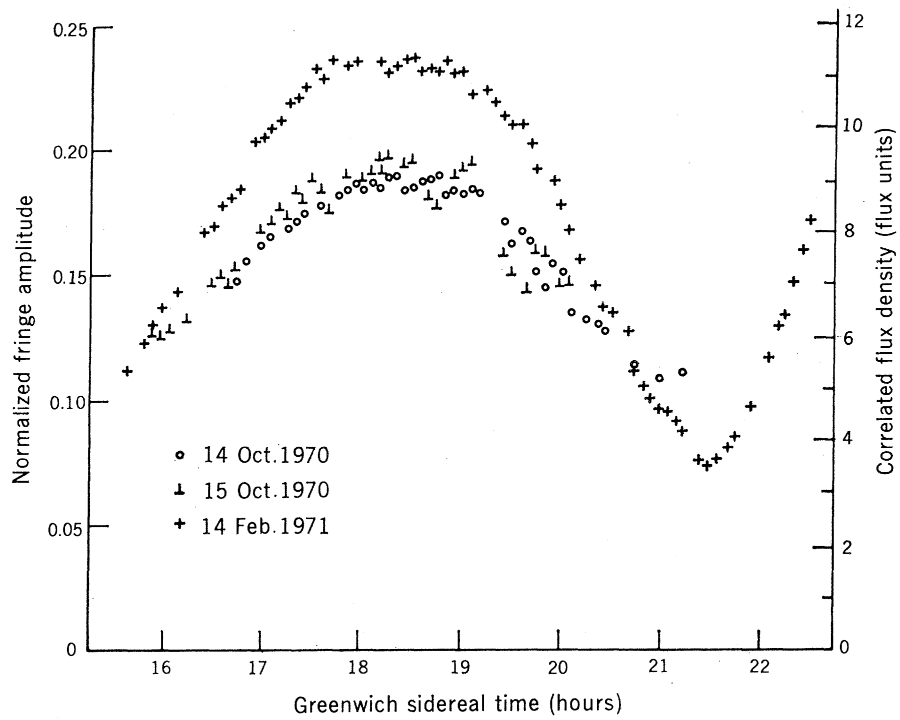

Fig. 2. Fringe-amplitude data from observations of 3C 273. Each point is based on 50 seconds of integration.

precise values are not significant since they are, as expected, highly correlated with the estimate ($\simeq 0.2 \times 10^{-3}$ arc sec) of the radius at half intensity of each component (*8*). The right ascension and declination separations found for the October epoch are reasonably consistent with our earlier results (*1*). The estimated rates of change of separation indicate that the two components of the double source are moving apart rapidly. Before giving quantitative results for this apparent expansion, we discuss the possible presence of systematic errors that may distort the fringe-amplitude patterns. For example, consider the observations during the last hour on 26 February as compared with those on 14 February; we would expect the ratios of the ordinates of the corresponding points during this period on these 2 days to be less, not greater, than unity. This expectation is borne out in Fig. 3, despite the fact that the postfit residuals have a root-mean-square value of only 0.004. These small, but definite, systematic trends demonstrate that the symmetric double source does not give a completely adequate representation of the data, or that the alleged systematic errors in the fringe-amplitude measurements are responsible for the trends, or both. Simply put, our interpretation may be more limited by systematic errors than by random ones.

In any event, the double-source model is clearly a reasonably good one. The largest fringe-amplitude residual is only 0.01 (Fig. 3), whereas the actual fringe amplitudes reach values as high as 0.25 (Fig. 1). We must therefore consider the key question: How reliable is a determination of differential expansion between the two components of this model? To test the reliability in a manner relatively free from the effects of the most likely systematic errors, we performed sensitivity studies that involved only the times of occurrence t_i of the nulls in the fringe-amplitude curves shown in Fig. 1.

From these times, the angular separations $\Delta\alpha$ and $\Delta\delta$ (*1*) were determined from the data for each day separately and their rates of change were determined from the combined data set (*9*). From the relevant analytically evaluated partial derivatives the sensitivity of each estimated quantity to an error in each t_i was found. These sensitivities show clearly, as does the least-squares solution, that the declination component of the separation rate is the most poorly determined quantity. This conclusion is not surprising since the resolution of the interferometer, determined by the projected baseline as shown in Fig. 4, is about five times greater in the $\Delta\alpha$ than in the $\Delta\delta$ direction.

On the basis of these sensitivity studies and a consideration of our results for several double-source models, we conclude that the angular separation between the two components of the putative double source has changed from $(1.55 \pm 0.03) \times 10^{-3}$ arc sec in October to $(1.69 \pm 0.02) \times 10^{-3}$ arc sec in February at an average rate of about $(1.2 \pm 0.3) \times 10^{-6}$ arc sec per day (*10*) with the position angle having remained nearly constant at about 36 ± 3 deg. The uncertainties given are based mainly on our estimate of the possible magnitudes of systematic errors in the data and are severalfold larger than the formal standard errors implied by the postfit residuals from the nine-parameter solution.

If we assume that this average rate of separation has remained constant during the past several years, we find that the two components coincided about 4 years ago—about 1967.4 $\pm$ 0.9. One may well ask whether any notable change was seen in the flux from 3C 279 within the 1966–1968 time period. The brightnesses observed at a variety of frequencies from 1964 to 1971 are shown in Fig. 5.

There appear to have been some dramatic changes in the microwave and optical fluxes during this period. The optical flux, in particular, increased by a factor of 6 between mid-1966 and late 1966. Whether the evolving structure detected by our interferometer is causally related to any of these flux changes is, of course, not clear. One cannot even eliminate from consideration relatively small changes in flux such as those that occurred in late 1967 to early 1968. These observations may represent, for example, the superposition of an old source of decaying flux and a new source of strongly increasing flux with the net increase thus concealing the true contribution of the new source.

From the rate of angular separation, we may also compute the corresponding component of the velocity of separation as it would be measured at the source. The appropriate distance to use to convert, by simple multiplication, the angular rate as measured by the observer to the transverse velocity component that would be measured at the source is given as a power series in z by

$$D(z,H,q) \simeq (1+z)^{-1} \times \frac{c}{H}\left[z + \frac{1}{2}(1-q)z^2 + O(z^3)\right] \quad (1)$$

for the Robertson-Walker metric (*11*), where z is the observed red shift of the object, H is the Hubble constant, and q is the deceleration parameter. This expression is very nearly model independent since it is based only on the assumption that the universe is homogeneous and isotropic. When $z \lesssim 0.5$ and $q \lesssim 1$, Eq. 1, despite the omission of higher-order terms, yields excellent agreement with the exact but model-dependent relation that follows from Einstein's equations for a matter-dominated universe (*11*). The constants H and q that appear in such relations are generally accepted to be about 75 km sec^{-1} $megaparsec^{-1}$ and no more than unity, respectively; by using these values we will obtain nearly a lower bound for D and hence for the separation velocity. Combining these values with the measured value of 0.538 for z for 3C 279 (*12*), we find that, on the basis of our symmetric double-source model, the apparent separation velocity can be no less than about 10 ± 3 times the speed of light (*13*)!

How can this startling result be understood? Although no definitive explanation can yet be given, we have considered the following possibilities (*14*): (i) Other, more complicated brightness distributions may give rise to the observed fringe-amplitude data without any parts appearing to move faster than c. For example, a symmetric model of three stationary point sources equispaced along a line yields reasonably good agreement with both the October and the February data, provided that the central source contributed only about 1 flux unit (that is, about 15 percent of the correlated flux) in October and essentially no flux in February (*15*). [Since this possibility and the other models we have considered (*16*) either seem too contrived or yield apparent velocities greater than c, we restrict the remaining alternatives to explanations based only on the results from the simple model of a symmetric double source.] (ii) The apparent speed of separation v_a may correspond to a phase, rather than a group, velocity. As one of a broad spectrum of possible illustrations of this type of effect, we mention a collision between two large, expanding spherical shells or one shell with a stationary plane. If intense, short-lived radio emissions in an optically thin medium emanate from the ring-shaped points of contact, then a distant observer whose line of sight is not too highly inclined to the plane

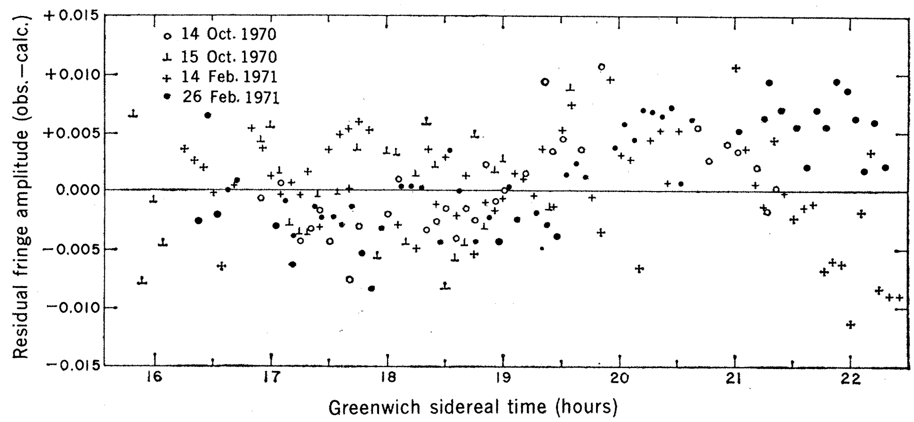

Fig. 3. Postfit fringe-amplitude residuals for the weighted-least-squares solution for a typical double-source model of 3C 279 (see text).

of the rings may see two "point" sources (with less intense connecting line sources) moving away from each other at an apparent speed that may be arbitrarily large depending on the elapsed time since the initial point contact. For shells with centers far apart as compared to a light year, v_a could exceed c by a large factor for a long time (*17*). (iii) Quasars may contain regions that "blink" on and off independently at radio wavelengths, and the pair observed in October may be totally different from the pair observed in February. (iv) The double source may, in fact, be a single pair of compact sources. If these sources were moving away from a common origin along lines inclined by less than 6 deg (*18*) to the observer's line of sight, then v_a could be greater than $10c$ with the actual separation velocity being less than c. (v) Scintillation, or multipath phenomena, may be involved; for example, a moving, inhomogeneous refractive medium interposed between, say, a single source and an observer could lead to a double image with the relative positions of the two varying with time. The apparent speed of separation could far exceed c if the characteristics and placement of the medium were suitable. Alternatively, the apparent motion of an actual double source could be magnified by an interposed medium. (vi) The distance to 3C 279 may be far less than 10^9 light years because its red shift may stem mostly from a non-

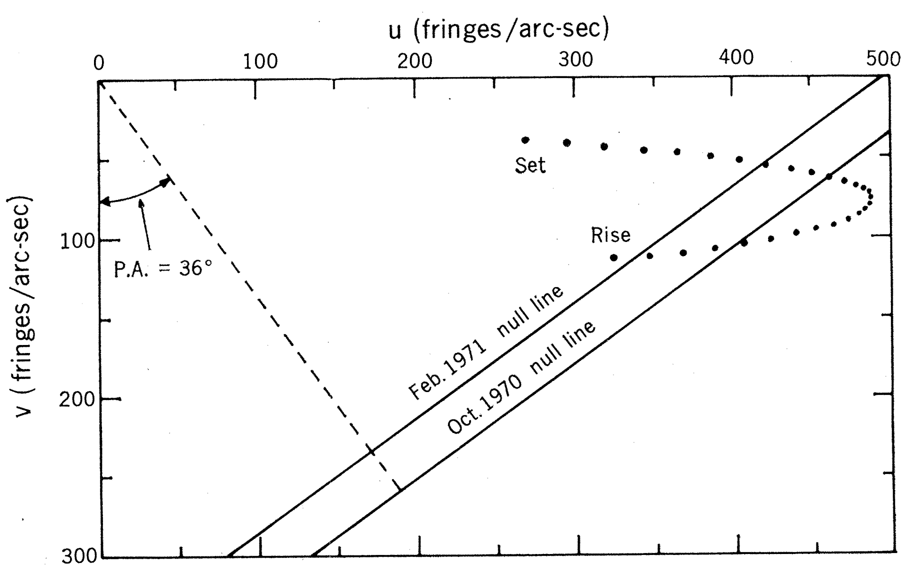

Fig. 4. The u-v plane (*1*) representation of the Goldstone-Haystack observations of 3C 279. The dotted curve shows the interferometer resolution at 15-minute intervals from 15 hours 30 minutes to 22 hours 30 minutes Greenwich sidereal time. The solid lines connect the times at which nulls were observed in October 1970 and in February 1971. The distances from the origin to the solid lines are inversely proportional to the separations of the components of the putative double source at the two times of observation. [The position angle (*P.A.*) was assumed to remain constant.]

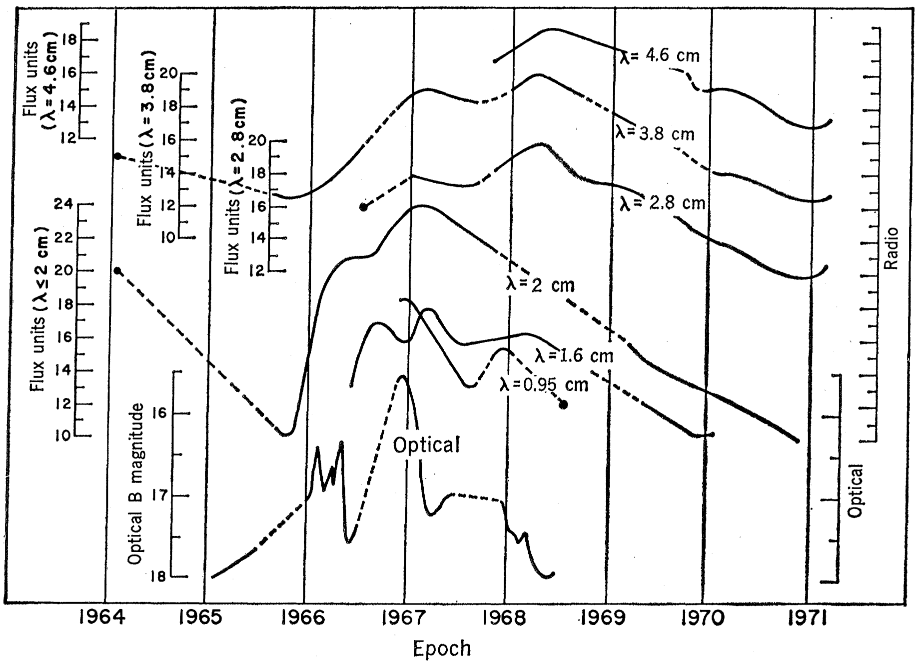

Fig. 5. Time variations of the flux from 3C 279 as measured at a variety of frequencies (*23*). The later occurrence at lower frequencies of the peaks in the flux curves is generally expected for expanding sources.

cosmological mechanism such as rapid motion with respect to the comoving reference frame. (vii) The Hubble constant may be greater by a factor of 10 than present-day estimates and may, in fact, be closer to Hubble's original value of about 500 km sec^{-1} $megaparsec^{-1}$. (viii) The universe may deviate so severely from large-scale conditions of homogeneity and isotropy that the Robertson-Walker and other conventional metrics may yield a seriously misleading association between red shift and distance. (ix) The "objects" observed may actually be moving at speeds in excess of c and may represent tachyonic matter.

Clearly, the last three possibilities, and especially the last one, cannot be taken seriously on the basis of the present observations. Unfortunately these observations are also too limited to enable us to distinguish reliably between any of the other alternatives. But enough data do exist to raise questions difficult to answer about each of our proposed explanations. Aside from the by now classic problems concerned with the origin of the enormous energy densities in quasar components, we mention a few specific samples: If a three-point-source model [see conjecture (i) above], or a minor variant, is responsible for the curves shown in Fig. 1, we are faced with the development of a reasonable physical mechanism that would yield such properly time-varying fluxes. For substantially different brightness distributions, we must then consider the following seeming coincidence: Observations of 3C279 made in January 1971 at a radio frequency of 2300 Mhz over a baseline almost identical to ours, when measured in wavelenghs, indicate the likely presence of a minimum in the *u-v* plane at a position (see Fig. 4) close to the line through the interpolated positions of the nulls obtained in our observations (*19*). If the observed objects represented regions in the source that "blinked" on and off independently [conjecture (iii)], it would be very difficult to explain how both components of the double source contributed so nearly equally to the correlated flux in October and again in February. Moreover, the apparent consistent change in the location of the second null between 14 and 26 February (Fig. 1) is hard to reconcile with this independent-region model. If a phase-velocity explanation [conjecture (ii)] is the correct one, it will still be necessary to construct a realistic model that yields equal brightness for the two observed components. Conjecture (iv) suffers much more from this same problem: If the components of the putative double source were moving highly relativistically in opposite directions from a common origin, red-shift effects on the apparent brightness would be expected to destroy the symmetry that might have been present in the 3C279 rest frame (*20*) rather than to create it from inherently asymmetric components. Furthermore, the idea that our view would be at an inclination angle $\theta \lesssim 6$ deg appears a priori to be unlikely. Even were one to postulate that a large number of objects were involved in an explosion but that only two were visible because of the extreme blue shifts of their radiation as compared to the shifts for the other objects (*20*), it still seems unlikely for the two to be so precisely directed relative to our (arbitrary) line of sight as to appear equally bright. A scintillation model [conjecture (v)], based on an interposed refractive medium, can be attacked on the grounds that if the medium were ionized, the flux variations (Fig. 5) seen at higher frequencies might be expected to be smaller than at lower frequencies. On the other hand, if the refraction were gravitational or due to a neutral medium, we might expect these variations to be independent of frequency. Figure 5 does not appear to be consistent with either interpretation (*21*). A possible noncosmological origin [conjecture (vi)] for the major fraction of the red shift of 3C 279 would have seemed more likely, were it not for the recent measurements of Gunn (*22*); one would seem now to be forced to conclude that there exist at least two classes of quasars. Making the Hubble constant larger [conjecture (vii)] raises the specter of having the earth older than the universe!

All in all, our nine suggested explanations may appear almost as dubious as the like number of lives of the proverbial felines. But further observations should at least serve to distinguish between many of these (and other) possible interpretations of the data. For example, measurements at different frequencies would relate to scintillation models and would extend the *u-v* plane coverage if the brightness distribution were not too frequency dependent; use of more baselines would allow a better determination of the brightness distribution at any given time; and observations at well-spaced intervals would allow the time-dependence of the brightness variations to be used as a discriminant. Certainly the astrophysicist's understanding of the fine structure and internal kinematics of quasars cannot help but benefit from extended series of these very-long-baseline interferometry experiments.

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References and Notes

1. C. A. Knight, D. S. Robertson, A. E. E. Rogers, I. I. Shapiro, A. R. Whitney, T. A. Clark, R. M. Goldstein, G. E. Marandino, N. R. Vandenberg, *Science* **172**, 52 (1971).
2. The equipment, procedures, and terminology were described and defined in (*1*) and will not be repeated here.
3. The unnormalized fringe amplitudes presented previously [see (*1*)] have now undergone preliminary normalization: The ordinates in Figs. 1 and 2 are now scaled to represent that fraction of the total observed flux which appears correlated.
4. The positions of the nulls in mid-February were confirmed by independent measurements made shortly after ours with the same interferometer [D. Shaffer, M. H. Cohen, G. Purcell, K. I. Kellermann, J. J. Broderick, D. L. Jauncey, as reported by D. L. Jauncey at the Rumford Symposium, Brookline, Mass., 13–14 April 1971; *Astrophys. J. Lett.*, in press].
5. The first null was not seen on 26 February because the observations of 3C 279 on that date started too late.
6. Although the nulls seem to dip down into the noise level, the fringe rate appears to vary smoothly throughout the null regions for the February data. This fact indicates that, even if the nulls are exact, the signal-to-noise ratio is sufficiently great to yield accurate results for the fringe rate only several minutes before and after each null.
7. The size of the components could not be estimated reliably from the October data because the observations (Fig. 1) did not extend over a sufficiently large fraction of the resolution range of the interferometer. The February data, as will be discussed, seem to imply that the components have nonnegligible sizes; their actual diameters, unfortunately, are not well determined because of (i) correlations with other parameters in the models, and (ii) the possible presence of systematic errors near the end of the observing day.
8. Moreover, as shown by studies of other models, we cannot distinguish the form of the brightness distribution of each component. Nor, in view of (*7*), can we discern any change in the size of the components between October and February.
9. These calculations were carried out only for the two-point-source model because of its simplicity and because the results are not sensitive to this choice among the possible symmetric double sources. For the two-point-source model, the time dependence $A(t)$ of the fringe amplitude is given by the easily derived formula:
$$A(t) = |K(t) \cos \frac{\omega b}{2c} \{\Delta\alpha(t) \cos\delta_s \times \cos\delta_b \sin(\alpha_{b_0} + \Omega t - \alpha_s) + \Delta\delta(t) \times [-\sin\delta_s \cos\delta_b \cos(\alpha_{b_0} + \Omega t - \alpha_s) + \cos\delta_s \sin\delta_b]\}|$$
where $K(t)$ is the maximum fringe amplitude; ω is the angular frequency at which the interferometer operates; b is the baseline length; c is the speed of light; $\Delta\alpha(t)$ and $\Delta\delta(t)$ are, respectively, the time-varying separation of the two points in right ascension and declination; α_s and δ_s denote the right ascension and declination, respectively, of the direction to the source region; α_{b_0} and δ_b are the right ascension (at $t = 0$) and declination, respectively, of the interferometer baseline; and Ω is the rotation rate of the earth which introduces the diurnal period into the behavior of the baseline vector. The fringe amplitude vanishes whenever the argument of the cosine is $(2n + 1)(\pi/2)$, where n is an (unrestricted) integer. From the times of occurrence of the two nulls and a given value of n, one can therefore solve the two simultaneous linear equations to obtain the corresponding values $\Delta\alpha$ and $\Delta\delta$ as functions of the t_i. The partial derivatives follow trivially and are easily transformed to obtain the corresponding ones for separation distance and position angle. Previous work (*1*) indicated $n = 0$ to be in best agreement with the data, and our discussion is restricted to that value. As an illustration of the behavior of the solution when the nulls change position, consider for simplicity only the $\Delta\alpha$ part of the argument of the cosine. The sine term for this part is a maximum at a time nearly midway between the nulls. The increase in separation of the nulls for the time period shown in Fig. 1 would therefore imply a decrease in the values of $\sin(\alpha_{b_0} + \Omega t - \alpha_s)$ at the times of the nulls in February as compared to its values at the corresponding times in October. For the total argument of the cosine to remain equal to $\pi/2$ at these times, $\Delta\alpha$ would have to increase proportionately.
10. This result was first mentioned, in abbreviated form, in (*1*) (see note added in proof).
11. See, for example, S. Weinberg, *The General Theory of Relativity* (Wiley, New York, in press).
12. C. R. Lynds, A. N. Stockton, W. C. Livingston, *Astrophys. J.* **142**, 1667 (1965); E. M. Burbidge and F. D. Rosenberg, *ibid.*, p. 1673. The sources of the spectral-line radiation that were used in these red-shift determinations most likely do not partake of the same motions with respect to the center of mass of 3C 279 as do the sources of continuum radiation detected with our interferometer. Hence these motions are ignored in our interpretation of z.
13. We recently learned of a paper by A. T. Moffet, J. Gubbay, D. S. Robertson, A. J. Legg, presented at the International Astronomical Union Symposium No. 44, Uppsala, Sweden, August 1970 (in press), in which the authors argued that a relativistic expansion with $\gamma \equiv (1-\beta^2)^{-1/2} \gtrsim 2$ might be taking place in 3C 279. Their argument was based on the assumption that the increase in the total 13-cm flux measured between November 1967 and December 1969 was related to an expanding component first seen at short-centimeter wavelengths in 1966 (see Fig. 5); from the fact that the increase in correlated flux over their 80-million-wavelength baseline over the same 2-year time period was 15 percent less than for the total flux, they inferred that the expanding component was being resolved, which would imply a relativistic expansion. {A previous inference by these authors of the relativistic expansion of a component within 3C 273 [J. Gubbay, A. J. Legg, D. S. Robertson, A. T. Moffet, R. D. Ekers, B. Seidel, *Nature* **224**, 1094 (1969)] was partially withdrawn in their International Astronomical Union paper because of the difficulty with the identification of a decrease in flux density with a presumed expanding component seen earlier at short wavelengths. In any event, although our 3C 273 data (see Fig. 2) exhibit striking changes between October 1970 and February 1971, we cannot interpret them reliably in terms of a relativistic expansion.}
14. These possibilities were first discussed by us at the Rumford Symposium, Brookline, Mass., 13–14 April 1971. Several of them have been advanced at one time or another to account for various quasar characteristics; however, the literature is too vast to permit one to even attempt to distribute credit properly. For a relevant bibliography through 1967 see K. I. Kellermann and I. I. K. Pauliny-Toth, *Annu. Rev. Astron. Astrophys.* **6**, 417 (1968).
15. Our normalization is too uncertain to enable one to discern reliably a decrease of 15 percent in the correlated flux between October 1970 and February 1971. In any event, one could explain the absence of such a decrease by assuming that the flux from the outer components each increased—independently (!) —by about 7 percent between the two observations and that their sizes also increased so as to be consistent with the February data. Of course, the greater the number of ad hoc assumptions, the less convincing the model.
16. We have also considered continuous brightness distributions such as a bar model and uniformly bright ellipses. Although these have not yet been investigated in nearly so much detail as the double-source models, our preliminary conclusions are twofold: (i) The time variations required to be consistent with both the October and February data also yield apparent velocities much greater than c; and (ii) these models seem to require nearly all, and in some cases an improper fraction, of the total flux in order to yield agreement with the fringe-amplitude values near the end of each observing day. In view of the many separate components observed in previous 6-cm studies of 3C 279 [see K. I. Kellermann *et al.*, *Astrophys. J.* **153**, L209 (1968)], it would be very surprising if almost all of the 3.8-cm flux were "tied" up in such a small region.
17. At present, our data are insufficient to permit us to determine all the parameters required, for example, by the model of a shell expanding into a plane. However, if we assume that the expansion is nonrelativistic and that our line of sight is not too highly inclined to this plane, then the apparent acceleration is given by
$$-(vR/2)^{1/2}t^{-3/2}$$
where R is the distance from the plane to the center of the shell, v ($<< c$) is the actual expansion velocity of the shell, and t is the observed time reckoned from the first instant that emissions created by the collision reach the observer. Using the apparent relative separation and velocity deduced above for the two components, we would expect a decrease of about 15 percent in this velocity by June 1971 on the basis of this model. In connection with such phase-velocity models, we note that the appearance to a distant observer of sources of emission whose excitation mechanism travels at speeds in excess of c can be quite bizarre. For example, consider two lines that form a blunt "flying wedge" with short-lived radio emissions being produced at the points of contact of the flying wedge and a plane surface. These contacts may simulate two point sources moving with an arbitrarily large separation velocity. If the line of separation between them is inclined to the observer's line of sight (*1*) and if the component along the latter line of the (phase) velocity of the "point" approaching the observer equals c, then, neglecting parallax effects, the point appears as a line since the light from all sequentially emitting points arrives simultaneously at the position of the observer. Moreover, if this component exceeds c, then to the observer the two sources will appear to be racing together rather than apart! (Following our discussion of such models at the Rumford Symposium, other variations were proposed by T. Gold, by M. J. Rees, and by A. Cavaliere, P. Morrison, and L. Sartori.)
18. From Eq. 1 (*1*), we see that $v_a \simeq 10c$ can be achieved with $(1 - \beta^2)^{-1/2} \simeq 10$ and $\sin\theta \simeq 0.1$ or $\theta \lesssim 6$ deg.
19. This result was presented by A. T. Moffet at the Rumford Symposium, Brookline, Mass., 13–14 April 1971. It is based on a sharp decrease in the fringe amplitude between results obtained up to December 1969 and a measurement made in January 1971; all measurements referred to a point in the *u-v* plane that lies near the position of our interpolated null line for January 1971.
20. M. J. Rees, remarks made at the Rumford Symposium, Brookline, Mass., 13–14 April 1971.
21. The variations in Fig. 5, of course, relate to

the total flux, whereas our observations are sensitive only to that fraction concentrated in small components.
22. J. E. Gunn, *Astrophys. J.* **164**, L113 (1971).
23. The optical flux measurements are from T. D. Kinman [*Science* **162**, 1081 (1968)] and the 0.95-cm data are from R. W. Hobbs, H. H. Corbett, and N. J. Santini [*Astrophys. J.* **156**, L15 (1969)]. The 1.6-cm data through 1968.0 were obtained by T. P. McCullough and J. A. Waak [*Astrophys. J.* **158**, 849 (1969)]; the data from 1969 onward were provided by R. W. Hobbs and J. A. Waak (personal communication). The 2-cm flux results up to 1968.0 are from K. I. Kellermann and I. I. K. Pauliny-Toth [*Annu. Rev. Astron. Astrophys.* **6**, 417 (1968)]; the data from 1969.2 to the present were provided by W. A. Dent and G. Kojoian (personal communication) and were obtained with the Haystack radio telescope. The 2.8-cm and 4.6-cm flux data are from B. H. Andrew, G. A. Harvey, J. L. Locke, J. M. MacLeod, and W. J. Medd (personal communication) and were obtained at the Algonquin Radio Observatory. The 3.8-cm fluxes were measured at the University of Michigan; the data before 1967 were obtained by W. A. Dent and are given, along with the data from 1967 through 1968.7, by H. D. Aller [*Astrophys. J.* **161**, 1 (1970)]; the data from 1969 onward were provided by H. D. Aller and E. T. Olson (personal communication). We thank all of the above astronomers for generously giving us permission to use their flux data prior to publication.
24. We thank C. Finnie, H. F. Hinteregger, G. Purcell, T. Sato, L. Skjerve, D. Spitzmesser, and the staffs of the Goldstone and Haystack facilities for assistance in the engineering and technical aspects of the experiment, and the Mathematics and Computing Branch, Space and Earth Sciences Directorate, Goddard Space Flight Center, for support. We also thank D. L. Jauncey of the Arecibo Observatory and W. E. Howard III of the National Radio Astronomy Observatory for the use of the Mark I recording systems, and C. C. Counselman III and J. M. Moran, Jr., for critically reading the manuscript. The M.I.T. Haystack Observatory and the M.I.T. experimenters are supported in part by grants from the National Science Foundation. The Jet Propulsion Laboratory is sustained by NASA contract NAS 7-100.

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Underground Nuclear Explosions: Tectonic Utility and Dangers

Abstract. *The tectonic strain energy released by several underground nuclear explosions has been calculated through an analysis of seismic surface waves. The proportionally great amount of energy released in certain events suggests the possible uses for, as well as the hazards of, underground testing.*

Seismic waves generated by underground nuclear explosions quite often indicate complications arising from the interaction of the explosive source with the surrounding inhomogeneous medium. The clearest evidence of such an interaction is the generation of horizontally polarized *SH* and Love waves by many explosions. The radiation patterns of these waves and the mechanisms of their generation have been the subject of a number of studies (*1–4*). It is generally agreed that an explosion detonated in a prestressed medium radiates some ambient strain energy because of relaxation around the cavity and extended cracks. The extent of this relaxation and the amount of energy released have not, however, been accurately determined.

The radius of the zone of relaxation and the amount of tectonic strain energy release are two characteristics of nuclear explosions that are of extreme importance. The first consideration that depends upon a knowledge of these characteristics is the feasibility of utilizing underground explosions for earthquake control. Explosions might be effective in periodically releasing accumulating tectonic strain energy in active areas and, thus, could possibly prevent major earthquakes. The second consideration concerns the safety of large underground explosions. An explosion that releases very large amounts of strain energy would have the same effect as that of a large earthquake. If larger devices are tested in new locations where ambient stress patterns are not known, the strain release problem becomes more critical. As a third point, the release of large amounts of preexisting strain energy may affect some (but not all) of the seismic discrimination methods between earthquakes and explosions.

The cases that have been studied to date indicate that some strain energy was released by most nuclear explosions detonated in relatively hard media (*5*). However, the strain energy released was less than the equivalent seismic energy of the explosions themselves in all but one case. The exception was Hardhat, detonated in granite. The excessive strain energy release in this case was attributed to the possible triggering of an earthquake (*2, 6*).

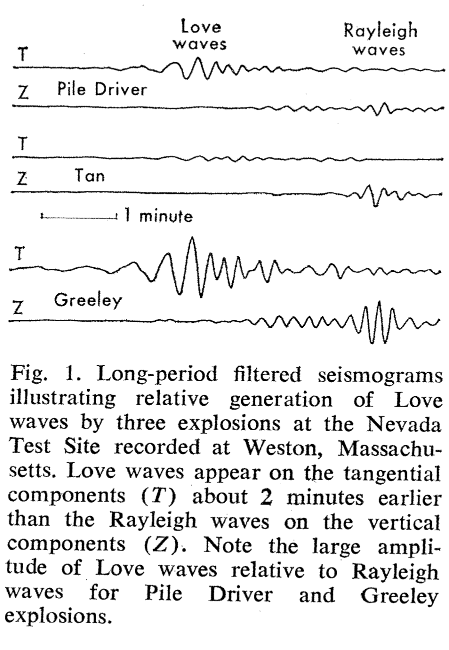

Fig. 1. Long-period filtered seismograms illustrating relative generation of Love waves by three explosions at the Nevada Test Site recorded at Weston, Massachusetts. Love waves appear on the tangential components (T) about 2 minutes earlier than the Rayleigh waves on the vertical components (Z). Note the large amplitude of Love waves relative to Rayleigh waves for Pile Driver and Greeley explosions.

We will report here on two other Nevada Test Site explosions (Pile Driver and Greeley), which generated large Love waves and released significant amounts of tectonic strain energy. Data from these events were obtained from LRSM (Long Range Seismic Measurements), WWSS (World Wide Standard Seismograph), and CSS (Canadian Standard Seismograph) system stations located throughout North America. The long-period records were digitized and filtered. The two horizontal components at each station were rotated to radial and tangential directions with respect to the explosions in order to separate the Love waves. The resulting tangential component (Love waves) and the vertical component (Rayleigh waves) were then Fourier-analyzed to obtain the amplitude spectra.

In Fig. 1, long-period seismograms of three explosions are illustrated. Tan, detonated near the other events, has been included as an example of a typical explosion that did not generate extensive Love waves. In this study both the radiation patterns of Rayleigh waves and the amplitude ratios of Love to Rayleigh waves were used to determine the strain energy release.

An explosion with associated tectonic strain release can be represented by a composite source consisting of an isotropic explosion component and a double-couple strain release component (*3, 7*). On the assumption that the time delay between the explosion and the strain release and the differences between time functions of Love and Rayleigh waves are negligible, expressions for Rayleigh and Love wave far-field displacements from such a composite source are given by

$$U_R(\omega) = C_R(\omega)(1 + F \sin 2\theta) \exp [i(\omega t - k_R r)]$$
$$U_L(\omega) = C_L(\omega) \cos 2\theta \exp [i(\omega t - k_L r)] \qquad (1)$$

where C_R and C_L are functions of frequency, distance, and the medium, ω is frequency, t is time, k_R and k_L are