Reports

Quasars: Millisecond-of-Arc Structure Revealed by Very-Long-Baseline Interferometry

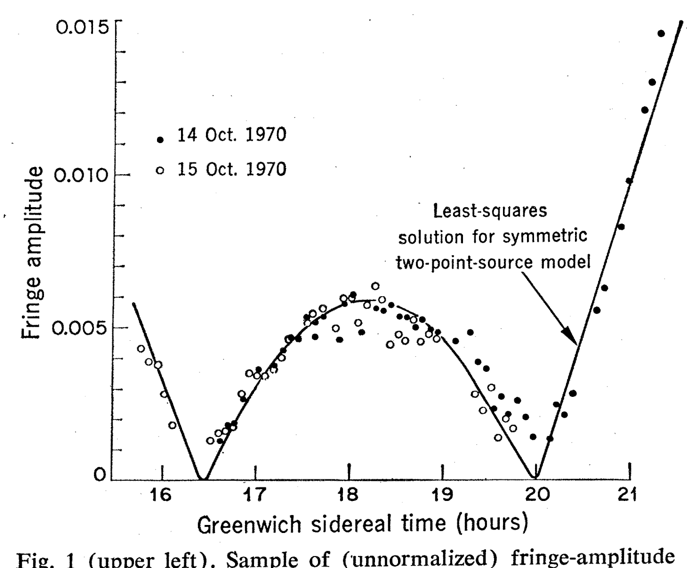
Abstract. *Observations with the Goldstone-Haystack radio interferometer of the quasars 3C 279 and 3C 273 have disclosed the presence of fine structure in their radio emissions. Although the interpretation is not unique, the fringe-amplitude data for quasar 3C 279 are quite consistent with emissions from two points, each contributing equally to the correlated flux. The separation of the two points is estimated to be* $(1.55 \pm 0.05) \times 10^{-3}$ *arc second, or about 20 light years at the distance of* 3×10^9 *light years inferred from optical red-shift data. The formal uncertainty in the right-ascension component of the separation is about* 6×10^{-6} *arc second; differential proper motion in this direction at half the speed of light could be discerned within a year. The fringe-amplitude data of quasar 3C 273 allow similar, but less definitive, interpretations.*

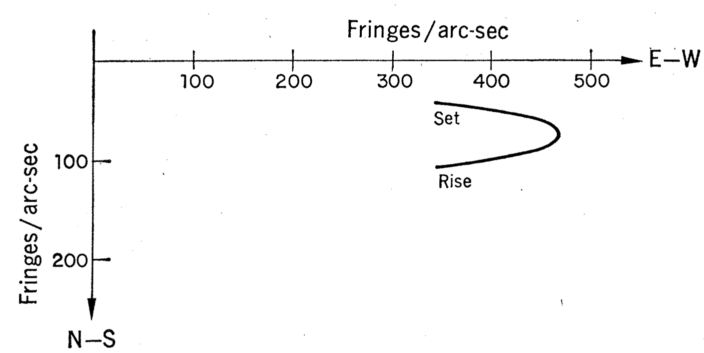
Even after a decade of intensive study, the nature of quasars and their sources of energy remain enigmatic. Quasars seem to yield their secrets only reluctantly. In this report we describe a tantalizing new clue to their small-scale structure revealed by very-long-baseline interferometry (VLBI).

The most sensitive radiometric system yet employed for VLBI (see Table 1) was used in October 1970 to observe the quasars 3C 279 and 3C 273. This interferometer was composed of the Goldstone "Mars" antenna and the Haystack radio telescope (baseline length $\simeq$ 3900 km) and was operated at a radio wavelength of 3.8 cm (7840 Mhz). Only 2 seconds of observation of quasar 3C 279 were required for the fringe-phase fluctuations attributable to system noise alone to drop below 10 deg. The primary purpose of the experiment was to detect the relative gravitational deflection of radio waves from these sources near the 8 October occultation of 3C 279 by the sun (*1*).

We observed each of the two quasars every 5 minutes for approximately five consecutive hours on each day from 1 through 6 October and 10 through 15 October. The coordinates assumed for these sources are shown in Table 2. The quasar signals received at each site, after passage through a low-noise maser amplifier, were mixed with local-oscillator signals derived from a hydrogen-maser frequency standard. After conversion to video, the signals were clipped, sampled, and recorded in the standard manner by means of the Mark I system (*2*). Two tape recorders were used at each site to allow nearly continuous observations; the raw data comprised about 1000 km of magnetic tape. The corresponding tapes from each site were cross-correlated to obtain the unnormalized fringe amplitude for each source for each observation. (By unnormalized fringe amplitude we mean the correlated fraction of the recorded bits.)

The pattern found for the fringe amplitude versus sidereal time for quasar 3C 279, illustrated in Fig. 1, was repeated with remarkable regularity ea h day except for the 4 days closest to solar occultation when few fringes were obtained. The portion of the curve preceding 16 hours 30 minutes was actually observed on only 1 day because of conflicting antenna schedules. How may this curve be interpreted? To obtain the brightness distribution of the source unambiguously to a certain resolution requires observations with baselines spaced properly over the half-plane normal to the line-of-sight to the source (*3*). Since our projected baseline





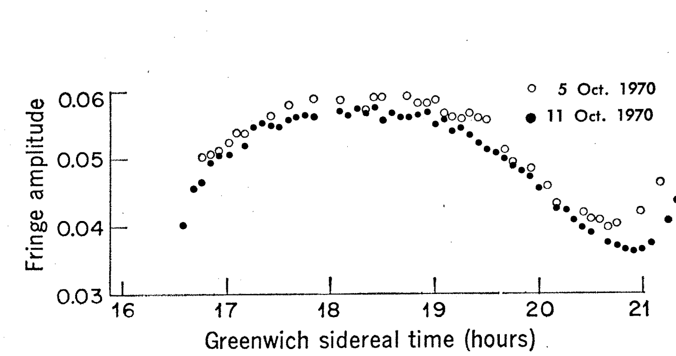


Fig. 1 (upper left). Sample of (unnormalized) fringe-amplitude data from observations of 3C 279 with the Goldstone-Haystack interferometer. Each point was based on 110 seconds of integration. Some of the scatter is attributable to the solar corona. Fig. 2 (upper right). Resolution of the interferometer in the east-west and north-south directions over the daily period of visibility of 3C 279 (*u-v* plane coverage). Fig. 3 (lower right). Sample of (unnormalized) fringe-amplitude data from observations of 3C 273. Each point was based on 50 seconds of integration.

Table 1. Characteristics of the interferometer.

Instrument	West longitude	North latitude (geodetic)	Altitude above mean sea level (m)	Antenna diameter (m)	Antenna gain (db)	System noise temperature (off source; zenith direction) (°K)	Frequency standard (for local oscillator system)	Recording system	Station time
Goldstone	116.89°	35.42°	1031	$\simeq 64$	72	$\simeq 27$	Hydrogen maser	NRAO * Mark I	Cesium clock
Haystack	71.49°	42.62°	145	$\simeq 36$	66.1	$\simeq 40$	Hydrogen maser	NRAO * Mark I	Rubidium clock

* National Radio Astronomy Observatory.

was changed only by the earth's rotation, we obtained results only along a one-dimensional path through this plane, as shown in Fig. 2. The interpretation of our fringe-amplitude curve can therefore not be unique, and we confine ourselves here to the simplest model consistent with the data: two point sources of equal strength. The existence of the "nulls" in Fig. 1 implies that the correlated fluxes from the two components are nearly equal; the spacing allows the separation and orientation of the components to be estimated (*3*).

We used a parameterization of this model and a standard least-squares algorithm to estimate the relative positions of the two sources and their associated fluxes. All of the data from 1, 2, 14, and 15 October were included in the analysis except for a few bad points and those for which the unnormalized fringe amplitude was below 0.002. For simplicity, the use of Rayleigh statistics was avoided by the deletion of these low fringe-amplitude points. On the basis of root-mean-square postfit residuals of 0.0006 for the fringe amplitudes, we found $\Delta\alpha = (0.907 \pm 0.006) \times 10^{-3}$ arc sec and $\Delta\delta = (1.26 \pm 0.04) \times 10^{-3}$ arc sec for the separations of the two components in right ascension and declination, respectively (*4*). The total angular separation between the two components is $(1.55 \pm 0.05) \times 10^{-3}$ arc sec with the position angle, conventionally defined, being 36 ± 1 deg. Independent reductions based on the separate use of the data of 1 and 2 October and those of 14 and 15 October yielded results consistent within these errors. The correlated flux associated with the pair represents a large fraction of the total flux observed at 8 Ghz from the quasar 3C 279 complex (*5*); the correlated flux from each of the two parts is equal to within about 5 percent. From a separate analysis we also find the location of the complex to be within several arc seconds of the values given in Table 2.

The fringe-amplitude curve for quasar 3C 273 exhibits a minimum but no nulls (see Fig. 3). Although the interpretation is certainly not unique, the data here too are quite consistent with a two-point source model.

What are the theoretical implications of these results? Spectral data obtained from optical observations of quasar 3C 279 indicate a red shift, $\Delta\lambda/\lambda_{\text{rest}}$, of 0.54 (*6*); when interpreted in the standard manner with the Hubble constant taken to be 75 km sec^{-1} megaparsec^{-1}, and q_o to be unity, this shift implies an "angular size" distance to quasar 3C 279 of about 3×10^9 light years. The separation of our two "point" sources projected on the plane perpendicular to the line-of-sight would therefore be about 20 light years.

If the fringe amplitudes are really caused by two compact sources and if they resulted from a fairly recent explosion (*7*), then differential proper motions might be detectable in a short time. For a separation rate half the speed of light, the change in differential right ascension would be discernible within a year. Of course, if the true "proper motion" distance were substantially less than the accepted value, the change would become apparent in an even shorter time. Similarly, if the recession speed v of each component relative to the origin of the explosion were close to that of light, the motion might be detected after a very short interval. Because the closer of the two components is viewed at its location at a time later than that for the more distant one, the apparent speed v_a of separation of the two components (when the observer is at rest relative to the center of the explosion) is

$$v_a = \frac{2\ v\ \sin\theta}{1-\beta^2\ \cos^2\theta} \qquad (1)$$

where θ is the angle between the separation direction and the earth-quasar line and $\beta \equiv v/c$ (*8*).

Other quasar models are also consistent with our fringe-amplitude results. As further examples, we mention small "hot spots," or flares, emanating from a larger body (*7*), and possible synchrotron radiation from electrons orbiting in a giant dipole field of the primary body. The projection of the dipole axis on the plane normal to the line-of-sight would, in the latter case, be perpendicular to the line joining the two "point" sources as is the case for the two most intense parts of the decimetric radiation observed from Jupiter (*9*).

Similar types of comments can be made with respect to our data for quasar 3C 273, but, in view of their less definitive interpretation in terms of point sources, we omit a detailed discussion. It is of obvious interest to continue observations of this kind, to include polarization measurements, and to extend such an observing program to other baselines, other frequencies, and other quasars.

Note added in proof: Recent observations have revealed significant

Table 2. Source positions and baseline coordinates (spherical coordinates of Goldstone relative to Haystack).

*Source positions (1950.0)**	
Right ascension, 3C 279	12 hr 53 min 35.82 ± 0.02 sec
Declination, 3C 279	−5 deg −31 min −7.65 ± 0.25 sec
Right ascension, 3C 273	12 hr 26 min 33.31 ± 0.03 sec
Declination, 3C 273	2 deg 19 min 54.7 ± 0.5 sec
Baseline coordinates	
Length	3899.92 km
Hour angle	7.05140 hr
Declination	−9.1448 deg

* From (*10*).

time variations in the structure of both quasars; in terms of the two-point-source model, the separation of the components of 3C 279 appears to have increased by about 10 percent in 4 months.

CURTIS A. KNIGHT
DOUGLAS S. ROBERTSON
ALAN E. E. ROGERS
IRWIN I. SHAPIRO, ALAN R. WHITNEY
Massachusetts Institute of Technology, Cambridge 02139
THOMAS A. CLARK
Goddard Space Flight Center, Greenbelt, Maryland 20771
RICHARD M. GOLDSTEIN
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103
GERARD E. MARANDINO
NANCY R. VANDENBERG
University of Maryland, College Park 20740

References and Notes

1. Results from this aspect of the experiment will be published separately.
2. See, for example, B. G. Clark, K. I. Kellermann, C. C. Bare, M. H. Cohen, D. L. Jauncey, *Astrophys. J.* **153**, 705 (1968).
3. J. D. Kraus, *Radio Astronomy* (McGraw-Hill, New York, 1966), and references cited therein.
4. These numbers are based on an assumed spacing of ½ fringe between the two components at the times of the nulls of the fringe-amplitude curve. An assumed spacing of 1½ fringes yields somewhat poorer agreement with the observations. In either case, the resultant spacings do not reflect certain small corrections which are still under investigation, but which will not affect our conclusions.
5. Total fluxes of about 13 flux units have been reported at 3.75 cm by I. I. K. Pauliny-Toth and K. I. Kellermann [*Astrophys. J.* **146**, 634 (1966)]. A more recent discussion of flux measurements in this wavelength region is given by H. D. Aller [*Astrophys. J.* **161**, 114 (1970)]. Since 1966, observations at 1.55 cm have indicated a general increase in the emission from about 15 to 17 flux units with "outbursts" occurring sporadically [T. P. McCullough and J. A. Waak, *Astrophys. J.* **158**, 849 (1969)]; these latter "outbursts" may be associated with the small components to which our measurements are sensitive. Our two "point" sources may also be related to the quasar 3C 279C and 3C 279D sources reported for observations at a wavelength of 6 cm over a baseline, in wavelengths, approximately equal to ours [K. I. Kellermann *et al.*, *Astrophys. J.* **153**, L209 (1968)]. J. J. Broderick *et al.* [*Sov. Astron. AJ* **14**, 627 (1971)] note also that their 6-cm VLBI observations between Green Bank, West Virginia, and the Crimea show a complex structure for quasar 3C 279 with about 4 to 5 flux units belonging to an unresolved component less than 0.6×10^{-3} arc sec in extent.
6. C. R. Lynds, A. N. Stockton, W. C. Livingston, *Astrophys. J.* **142**, 1667 (1965); E. M. Burbidge and F. D. Rosenberg, *ibid.*, p. 1673.
7. Explosion and ejection models of quasars are fairly numerous; see, for examples, S. A. Colgate, *Astrophys. J.* **150**, 163 (1967); P. A. Sturrock, *Nature* **211**, 697 (1966); D. M. Mills and P. A. Sturrock, *Astrophys. Lett.* **5**, 105 (1970); M. J. Rees, *Mon. Notic. Roy. Astron. Soc.* **135**, 345 (1967).
8. Note that for $\beta^2 < 0.5$, v_a is a maximum for $\theta = \pi/2$. For $\beta^2 \geq 0.5$, v_a is a maximum for
$$\sin^2\theta = (1-\beta^2)/\beta^2$$
whence
$$v_a = c/(1-\beta^2)^{1/2}$$
A discussion of corresponding formulas for the appearance of uniformly expanding shells was given by M. J. Rees [*Nature* **211**, 468 (1966)].
9. See, for example, G. L. Berge, *Radio Sci.* **69D**, 1552 (1965).
10. Coordinates were obtained from J. Kristian and A. Sandage [*Astrophys. J.* **162**, 391 (1970)]. See also: C. M. Wade, *ibid.*, p. 381; A. Sandage, J. Kristian, C. M. Wade, *ibid.*, p. 399.
11. We thank B. F. Burke, H. T. Howard, H. F. Hinteregger, G. Purcell, T. Sato, L. Skjerve, D. Spitzmesser, R. Sydnor, and the staffs of the Goldstone and Haystack facilities for vital assistance in the engineering and technical aspects of the experiment, and the Mathematics and Computing Branch of the Space and Earth Sciences Directorate and the Manned Space Flight Network Data Evaluation Branch of the 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 their Mark I VLBI recording systems, the staff of the Pioneer Project of the Ames Research Center for cooperation in scheduling, and R. Vessot and M. Levine for assistance in the use of the Smithsonian Astrophysical Observatory's hydrogen-maser frequency standard which provided an independent check on the performance of Haystack's maser standard. 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 under NASA contract NAS 7-100.

15 March 1971

An Early Center of Bovine Husbandry in Southeast Asia

Abstract. *Non Nok Tha is a prehistoric site in northeast Thailand. The radiocarbon dates suggest that it was first occupied by at least 3500 B.C., and possibly as early as 5000 B.C. The deepest levels contain unexpectedly early evidence for rice cultivation and bronze casting. Multivariate and cultural analyses of the bovine bones suggest that the first inhabitants raised domesticated cattle. This is among the earliest evidence for bovine domestication known.*

The potential importance of southeast Asia as a major center of economic innovation during the prehistoric period was suggested theoretically by Sauer but has only recently been recognized archeologically (*1*). Gorman (*2*) has discovered early evidence for horticulture at Spirit Cave (in northern Thailand), and excavations at Non Nok Tha in northeast Thailand have led to the recognition of a unique and indigenous bronze-working tradition by about 3500 B.C. (*3*). This date has been obtained from a carbon sample located in a 1966 grave typologically identical to a 1968 grave containing a socketed metal tool (5370 ± 320 years old, sample GaK 1034). Moreover, Bayard has recently discovered rice-chaff temper in the earliest pottery from Non Nok Tha (*4*). Although the age of the level in question is unknown, ^{14}C dates from overlying levels suggest an antiquity of at least 3500 B.C., and possibly as much as 5000 B.C. Non Nok Tha has thus produced the earliest known evidence for rice cultivation and the earliest cast bronze implements east of the Tigris-Euphrates Valley.

The early levels of Non Nok Tha contain human burials associated with animal bones. The animal bones have been studied at the Department of Anthropology, University of Otago (*5*). The presence of articulated limb bones of bovines, suids, and canids makes it essential to ascertain their economic and generic status. This report concentrates on the bovine bones for the following reasons: (i) it was possible to collect modern, sexed comparative bone samples of water buffalo (*Bubalus bubalis*) and zebu (*Bos indicus*); and (ii) bovines were of potential economic importance as sources of meat and traction (*6*). Although domestic cattle in southeast Asia can pull light wheeled vehicles, only the water buffalo has the strength necessary to draw a plow through wet paddy fields. The intimate connection between the water buffalo and wet rice agriculture in southeast Asia is well known (*7*).

The prehistoric bovine limb bones from Non Nok Tha may belong to any of the following, either singly or in combination: *Bubalus bubalis* (water buffalo), *Bibos gaurus* (gaur), *Bos sondaicus* (banteng), *Bos indicus* (zebu), or *Bos sauveli* (kouprey). Wild or domesticated animals, or animals undergoing domestication, could be present. Sexual di- or trimorphism, as in the case of castrated animals, are further complicating factors (*8*).

There is no known modern comparative collection of either *Bos sondaicus* or *Bos sauveli*. Moreover, both species are extremely rare. Select bone dimensions from three specimens of gaur have been collected, together with the metacarpals, magna, and first fore phalanges of 38 female water buffalo and of 18 adult female zebu from Thailand, and the same bones were collected from 40 cows of Aberdeen Angus (Australian specimens) and 38 cows of Red Danish breed (Danish specimens).

The magnum and first fore phalanx