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THE NATURE OF THE LIGHT VARIATIONS IN THE DOUBLE QSO Q0957+561[1]

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ABSTRACT

Photographic photometry of Q0957+561 shows that during the 1980 and 1981 observing seasons, the northern image remained at nearly constant brightness, while the southern one showed a rapid brightening followed by a slow, nearly exponential fading. The speed of variation and shape of the light curve suggest that the observed variations are due to intrinsic variability of the imaged QSO, rather than to effects of stars in the lens galaxy. The differential time delay must be greater than 2.7 years. Archival plates taken early in this century show both components brighter by about 0.5 mag, demonstrating variability on long time scales.

Subject headings: quasars

I. INTRODUCTION

The double QSO Q0957+561 was originally suspected to be a pair of gravitational images of a single object based on the great similarity of the images' optical spectra (Walsh, Carswell, and Weymann 1979). Further optical observations confirmed and extended this conclusion, both with more detailed spectrophotometry (Weymann *et al.* 1979; Wills and Wills 1980) and by identification of a galaxy with properties appropriate for the gravitational lens (Young *et al.* 1980; Stockton 1980). Within a relatively short time, the same flux ratio of the images was observed at wavelengths from 2200 Å (Gondhalekhar and Wilson 1980) to 74 cm (Noble and Walsh 1980), an important property of the gravitational lens hypothesis. The time period during which these measurements were made was fortunate, as shortly thereafter significant variation began in both optical and radio flux, and in optical spectral properties (Miller, Antonucci, and Keel 1981; Greenfield, Burke, and Roberts 1980). The existence of such variations made determination of the differential delay between the two imaging paths a likely possibility. This measurement could provide an additional constraint on the detailed lens geometry and effect of the cluster of galaxies surrounding the lens galaxy, since models incorporating various assumptions about these predict differential delays ranging from a few weeks to decades. The most detailed model predicts a delay of about 5 years, with the southern (image B throughout this paper) being observed to vary later (Young *et al.* 1981; Dyer and Roeder 1980).

To explore this possibility, a program of photometry of Q0957+561 was undertaken at Lick starting near the time the first optical variations were observed. This paper presents the results of that program to date, as well as measures of archival plates in the Lick files, and discusses the interpretation of photometric variations in these images.

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II. OBSERVATIONS AND REDUCTIONS

Because the QSO images are relatively faint, and given limitations on available equipment and scheduling, photographic methods were used in this investigation. Photographic plates are particularly suitable for determination of the flux ratio of the components, as they have nearly equal brightness, identical colors, and small separation of the images. The declination of +56° allows observations from mid-northern latitudes for nine months of the year at zenith distances of 60° or less, while the north-south image separation removes problems of contamination due to atmospheric dispersion even at large hour angles.

The new plates obtained in this program were taken with the 0.9 m Crossley reflector (f/5, 38″.6 mm^{-1}), using preflashed 103a-O emulsion and a GG-13 filter to closely approximate the standard *B* bandpass. Exposures were 30 minutes in length. Images on the plate are generally less than 2″ in diameter, and in no case is there visible overlap or contamination of the QSO images. Other plates available for this study are three Crossley plates from 1902 to 1915 and a Lick 0.5 m astrograph plate from 1980 March. The treatment of these is described in detail below.

All plates were measured on the Lick Sartorius iris photometer, as modified by Oliver and Kinman (1964) for large-scale plates. The iris readings were calibrated using a new photoelectric sequence, observed in two parts. The brighter stars were observed for both color and magnitude with the Crossley in 1980 March. The fainter stars were measured in *B* only, using the same filter and photomultiplier at the 1 m Nickel reflector, taking advantage of the acquisition TV and computer offset features of this telescope to reliably set on faint stars. Experience has shown that color-dependent errors in these measures (those for which no color is given) are less than 0.04 mag for any likely stellar colors. The adopted photometric properties of the sequence stars are listed in Table 1, and the stars are identified in Figure 1 (Plate 1). The errors in Table 1 include the internal scatter of measures of each

TABLE 1

PHOTOELECTRIC COMPARISON SEQUENCE FOR Q0957+561

Star	B	$B-V$
1	13.25 ± 0.03	0.42 ± 0.03
2	14.56 ± 0.05	0.54 ± 0.03
3	14.79 ± 0.05	0.48 ± 0.03
4	14.90 ± 0.05	0.57 ± 0.03
5	15.62 ± 0.05	0.86 ± 0.04
6	15.92 ± 0.07	...
7	16.25 ± 0.07	...
8	16.66 ± 0.10	...
9	17.25 ± 0.15	...
10	17.38 ± 0.15	...
11	17.63 ± 0.15	...
12	17.66 ± 0.09	...
13	17.83 ± 0.20	...
14	17.88 ± 0.20	...
15	18.39 ± 0.20	...

star, photon statistics, and reproducibility of standard star measures.

The measured QSO image magnitudes on the archival Crossley plates are considerably brighter than recently observed. Because of changes in the photographic system, the treatment of these images deserves special comment. One plate (1902 February) was out of focus, blending the QSO images, and was not measured; the visual impression is that the images were nearly the same as in the 1903 plate. The early Crossley plates were taken on untreated, blue-sensitive emulsions with no filter, with the primary mirror silvered rather than aluminized; the bandpass effects of these differences from the modern plates roughly cancel due to the poor ultraviolet reflectivity of silver, which acts to some extent as a UV-blocking filter. Because of their flat energy distributions, the QSO images will appear brighter if the bandpass is even slightly bluer than that of the modern plates. Examination of the reflectance curve of a silver film (Jenkins and White 1976) indicates that magnitude differences due to bandpass changes should be 0.2 mag or less. The increased brightness early in the century seems to be real, rather than an artifact of the different photographic conditions.

Both sets of archival Crossley images are strongly comatic, since the plates were centered on the nearby galaxy NGC 3079, placing the QSO images near the edge of the field; only in the 1915 plate do the images overlap. The effect of the comatic tail of image B on the measurement of A was estimated from star measurements at various places on the plate, but the derived magnitude incorporating this correction is somewhat uncertain because of the high contrast and nonlinearity of this emulsion.

The 1980 March astrograph plate, part of the regular proper-motion program, was on 103a-O emulsion with no filter. Kinman (1968) found that the O-emulsion sensitivity, combined with the lens transmission of this instrument, yields magnitudes within a few hundredths of standard B measures, even for objects with quite nonstellar spectra. Because of the smaller scale of the astrograph plate, an enlarged duplicate was measured. A coarse wire grating over the objective produced higher-order images to the north and south of bright objects. One comparison star was omitted because of contamination by such an image, but these should produce no appreciable effect on the QSO image magnitudes.

The measured magnitudes are summarized in Table 2. Since it is better determined than the individual magnitudes (see below), the difference between the images is also tabulated. The measures of image A are consistent with a constant magnitude of 17.58 and typical error per plate of 0.09 mag, very nearly the error derived in a different way below. They show no significant trend with time, leading to the conclusion that image A showed no long-term variations of amplitude greater than 3% during the period 1980.3–1981.5. No significant short-term (night to night) variations were found in either image, but as the present data are not adequate to properly address this question, all discussion here concerns variations occurring over months.

Assessment of the errors in measurement and reduction is important, but not as straightforward as is the case with photon-counting detectors. To minimize errors in the iris measurements, the QSO images were measured alternately several times on each plate, and the same beginning and end standard stars overlapped during each plate measurement to check for drift in the iris photometer properties. Despite these precautions, inevitable errors are present in the iris readings themselves of about 0.03 mag. Evaluation of the error in plate reduction, in addition to that from measurement, from the scatter of standard stars about the calibration curve will lead to a sizable overestimate, since the photometric errors for single faint sequence stars are not small compared to

TABLE 2

B MAGNITUDES OF Q0957+561

DATE (UT)	NUMBER OF PLATES	IMAGE A	IMAGE B	ΔB
1903 May 30	1	16.88	17.51	0.63
1915 Jan 22	1	16.48	17.01	0.53
1980 Mar 20	1	17.54	17.72	0.18
May 18	1	17.56	17.55	−0.01
Jun 7	2	17.62	17.35	−0.27
Jun 21	1	17.46	17.34	−0.12
Oct 11	2	17.48	17.41	−0.07
Nov 8	1	17.45	17.20	−0.25
Nov 9	2	17.59	17.53	−0.06
Dec 12	2	17.54	17.53	−0.01
Dec 13	1	17.59	17.52	−0.07
1981 Jan 4	1	17.57	17.72	+0.15
Jan 5	2	17.57	17.64	+0.07
Apr 6	2	17.77	17.71	−0.06
Apr 7	2	17.64	17.62	−0.02
May 4	2	17.71	17.71	0.00
Jun 1	2	17.50	17.60	+0.10
Jun 24	1	17.65	17.76	+0.11
Jun 25	1	17.62	17.56	−0.06

individual plate measurement errors. In addition, uncertainty in the exact shape of the calibration curve may induce errors in the magnitudes themselves (but much less in the magnitude differences).

Because of these factors, the plate errors were evaluated by measuring the scatter about the mean on nights when multiple plates were taken. For nine nights with multiple plates, the rms scatter (error per plate) is 0.08 mag averaged over both QSO images; this may be seen by inspection of the individual measured magnitudes, listed in Table 3 for nights with two plates each. The same quantity evaluated for all plates in two-night runs is 0.09 mag; this is the value adopted for plates taken under ordinary conditions, and should include the contributions of all the sources of error mentioned above. This figure is further supported by measurements of an 18th magnitude field star not observed photoelectrically, measured once per plate (instead of three times as for the QSO images), which have an rms scatter of 0.11 mag when reduced in the same way as the QSO images. A zero-point error in the photometric system could exist, but would not affect the conclusions of this paper. The rms scatter on single nights of the magnitude difference (B − A) is only 0.06 mag, indicating that a significant portion of the error derived above for each image is due to the changeable shape of the calibration curve. This curve was treated as perturbations to the best-fit straight line; the perturbations were often no greater than the error of a single standard magnitude, so that only features in the curve large enough to encompass several standards could be accounted for. For this reason, plus the apparent constancy of light from image A, the remainder of this discussion deals with magnitude differences or flux ratios.

The light curve of image B is presented in Figure 2,

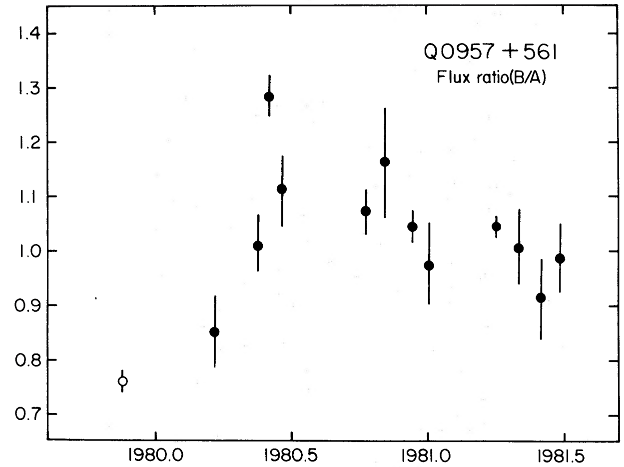

FIG. 2.—Light curve of Q0957+561 B, shown as a ratio of fluxes (B/A) in the blue. Errors are assigned as discussed in the text. Data on successive nights have been averaged. The open circle represents the measurement of Young *et al.* (1980).

using the magnitude differences of Table 2 converted to units of flux ratio. The error bars reflect the error of the mean when multiple plates were taken and the single-plate error of 0.09 mag otherwise, except for one plate obtained under poorer conditions for which the large standard star scatter indicated a larger error. No correction has been made for the contribution of the lens galaxy to the measured light of image B. The integrated value of $R = 18.5$ and $z = 0.36$ (Young *et al.* 1981) and K-correction appropriate to a "red" elliptical (Coleman, Wu, and Weedman 1980) indicate that the galaxy's blue integrated magnitude is about $B = 22.5$. At most, the galaxy contributes about 1% of the light, and most of this contribution was included in the 2″–3″ projected iris opening generally used. These fluxes refer essentially to the continuum. One line, C III] λ1909 at an observed wavelength of 4600 Å, contributes to the observed flux, but has an equivalent width varying from 32 to 58 Å in the observed frame (Miller, Antonucci, and Keel 1981), contributing only 3–6% of the measured flux. If the line flux is constant, the continuum variations would be slightly greater than those shown in Figure 2. The spectrophotometry referred to above, plus observations with the 1.5 m Mount Lemmon reflector in 1981 February, are consistent with constant line fluxes throughout the photometric variations, but no correction to pure continuum fluxes was performed because it is model-dependent and not important to the conclusions of this paper.

An external check on the reliability of these measurements is available in the photoelectric photometry of Beskin, Neizvestnij, and Shvartsman (1980) on two nights immediately following one on which plates were taken (1980 October 11). The agreement in magnitude differences is excellent—0.07 here versus 0.04 and 0.07 in their work. The magnitudes themselves, as might be expected, agree less well (within 0.2), but this indicates that the present system is free of gross systematic errors.

TABLE 3

B MAGNITUDES OF Q0957+561 FROM INDIVIDUAL PLATES

	IMAGE	
DATE (UT)	A	B
1980 Jun 7	17.51	17.30
	17.49	17.38
Oct 11	17.36	17.38
	17.47	17.36
Nov 9	17.52	17.49
	17.56	17.53
Dec 12	17.50	17.48
	17.50	17.51
1981 Jan 5	17.54	17.57
	17.62	17.71
Apr 6	17.68	17.60
	17.68	17.65
Apr 7	17.60	17.51
	17.63	17.69
May 4	17.47	17.64
	17.62	17.58
Jun 1	17.43	17.44
	17.44	17.65

III. INTERPRETATION

The overwhelming evidence in favor of the gravitational lens interpretation of Q0957+561 and the success of models in reproducing the observed configuration make any alternative to this picture most unlikely, as do dynamical problems in treating the two as distinct objects (Weymann *et al.* 1979). Therefore, in what follows, this picture is assumed.

Flux variations in the components of Q0957+561 might result either from variations in the imaged QSO or some change in the imaging geometry, which might in turn be secular or transient. Secular variations, due to progressive changes in the Earth-galaxy-QSO alignment or the relative positions of galaxies in the cluster about the lens galaxy, would be extremely slow except when the beam forming one image crosses a critical radius for imaging (caustic). Such an event would happen only once or twice, so its observation would be extremely unlikely.

Two kinds of changes in the lens properties over periods of years have been envisioned. Both result from motions of individual stars across an imaging beam, with a star itself producing additional amplification, or (very near a caustic) dramatically changing the amplification produced by the whole galaxy.

The effect of stars in the lens galaxy acting as focusing elements has been studied by Young (1981). Under plausible conditions, he finds that such events can give 50% perturbations in the continuum flux over times of about a century. Emission-line fluxes are largely unaffected, as they originate in a much larger region. In none of his simulations do variations occur on the time scale of months, the shortest over which they are seen.

If the light path forming image B lies close enough to a caustic, individual stars could shift it enough to change the total amplification (Burke 1981). Such variations are much faster than those due to direct effects of stars, while having comparable amplitudes. The image and beam sizes appropriate to Q0957+561 (Young 1981) make it likely that this would also affect only the continuum flux, complicating any attempt to separate intrinsic (QSO) variations from those due to stellar effects, as variations in QSOs also occur in the continuum with line fluxes remaining constant (see, for example, Visvanathan 1973; Netzer *et al.* 1979; Miller and French 1978). This is indeed the case in Q0957+561 (Miller, Antonucci, and Keel 1981). Any attempt to unambiguously specify the nature of the flux variations here must use information in addition to that provided by a table of fluxes and equivalent widths of lines. Some such information is available in the time scales of variations and the shape of the light curve in Figure 2.

As Young (1981) points out, the observed variations are much too rapid to be due solely to focusing effects of passing stars. It is more difficult to rule out Burke's (1981) model of stars triggering changes in image amplification, though several individually inconclusive arguments are available. Operation of this mechanism requires a privileged position in the imaging geometry; while image B is formed close to the caustic, giving it greater brightness than might have been expected (from the models of Young *et al.* 1980, 1981), it is not likely that we are as close as required. Also, the light amplification produced by any single star is symmetric in time. The light curve presented here is notably asymmetric, especially when the earlier data of Young *et al.* (1980) at 1979.9 are included. To duplicate this would require just the right combination of stellar masses, impact parameters, and velocities in a multi-star combination, introducing another degree of improbability. This model predicts continual variations because of the expected large number of stars in and near the image-forming beam. This does not seem to have been the case recently, since the constant brightness ratio observed before the onset of variations was at the value of 0.77 ± 0.03 given by spectroscopic observations to be produced by the gravitational lens when no variations in the QSO are complicating the interpretation; this is known from equivalent width measurements (Young *et al.* 1981).

The great variety of behavior displayed by the variations in QSOs (see, for example, Oke 1967 and Pollock *et al.* 1979) makes detailed comparison with particular objects of dubious value. At best, the fact that the speed and amplitude of the variations in Q0957+561 are well within the ranges of properties seen in variable QSOs is consistent with the idea that we are here seeing the variations of the imaged QSO in a relatively undisturbed manner.

Given the constant brightness of image A, it is obviously premature to draw conclusions about the differential delay time between images A and B, beyond the straightforward observation that the delay, in either sense, must be greater than 1.7 years from the present data alone. This limit may be extended to about 2.7 years by extrapolating image B's rate of fading and using the measures of flux ratio by Young *et al.* (1980) and Roberts, Greenfield, and Burke (1979), which show that it was not significantly different from 0.77 as early as 1979.48. This does not conflict with the detailed models of Young *et al.* (1981), but is in direct disagreement with models embodying a more schematic treatment of the cluster effects (Dyer and Roeder 1980).

Because of the small number of archive plates available, it is impossible to say definitely whether the brighter images in the past resulted from QSO or lens behavior. From this viewpoint, it is unfortunate that NGC 3079 did not seem more interesting at the turn of the century; a few more well-spaced plates might have yielded the differential delay with no further observations. These measurements do establish the existence of variability over decades; the fact that both images have faded suggests that this, too, is a manifestation of variability intrinsic to the QSO.

Note that, while the modern measurements of image B are nearly as bright as that on the 1903 plate, the brightness of B has recently been enhanced relative to that of A by a QSO event. The conclusion of greater past brightness refers strictly to the pure imaging situation in the absence of short-term QSO contributions. The archival-image brightness ratios suggest that no strong variations affected the images over a time scale less than the delay time.

The fact that star-induced changes in the lens properties can have the same spectroscopic character as variations in the QSO itself make it worthwhile to search for the differential delay polarimetrically. Since the principle of equivalence guarantees that polarization is not affected by gravitation under any conditions of relevance here (e.g., Weinberg 1972), the focusing action of the cluster, lens galaxy, or stars will not induce changes in polarization, especially since polarization variations occur in the continuum. The dominant E or cD character of the lens galaxy, and low limits on reddening within it (Young *et al.* 1980), imply that interstellar polarization, and any spatial variation of it, will not be a complicating factor. While current evidence for polarization variability of Q0957+561 is marginal (Miller and Antonucci 1981), the known flux variability and potential of polarimetry in unraveling the various effects operating on the total flux of each image makes further polarimetry, at optical and short radio wavelengths, well worthwhile.

IV. CONCLUSIONS

From 1979.5 to 1981.5, Q0957+561 A has remained constant, or nearly so, in brightness. The B image underwent an outburst of amplitude 0.45 mag followed by slow fading. This likely represents an event in the imaged QSO.

Analysis of archive plates shows that both images were brighter in 1902–1915 than recently, demonstrating the existence of long-term variations.

The spectroscopic effects of flux variations produced by stellar effects in the lens galaxy (or elsewhere along the line of sight) are quite similar to those produced by variation of the QSO itself. If the QSO is a polarization variable, polarimetry could help to untangle these effects.

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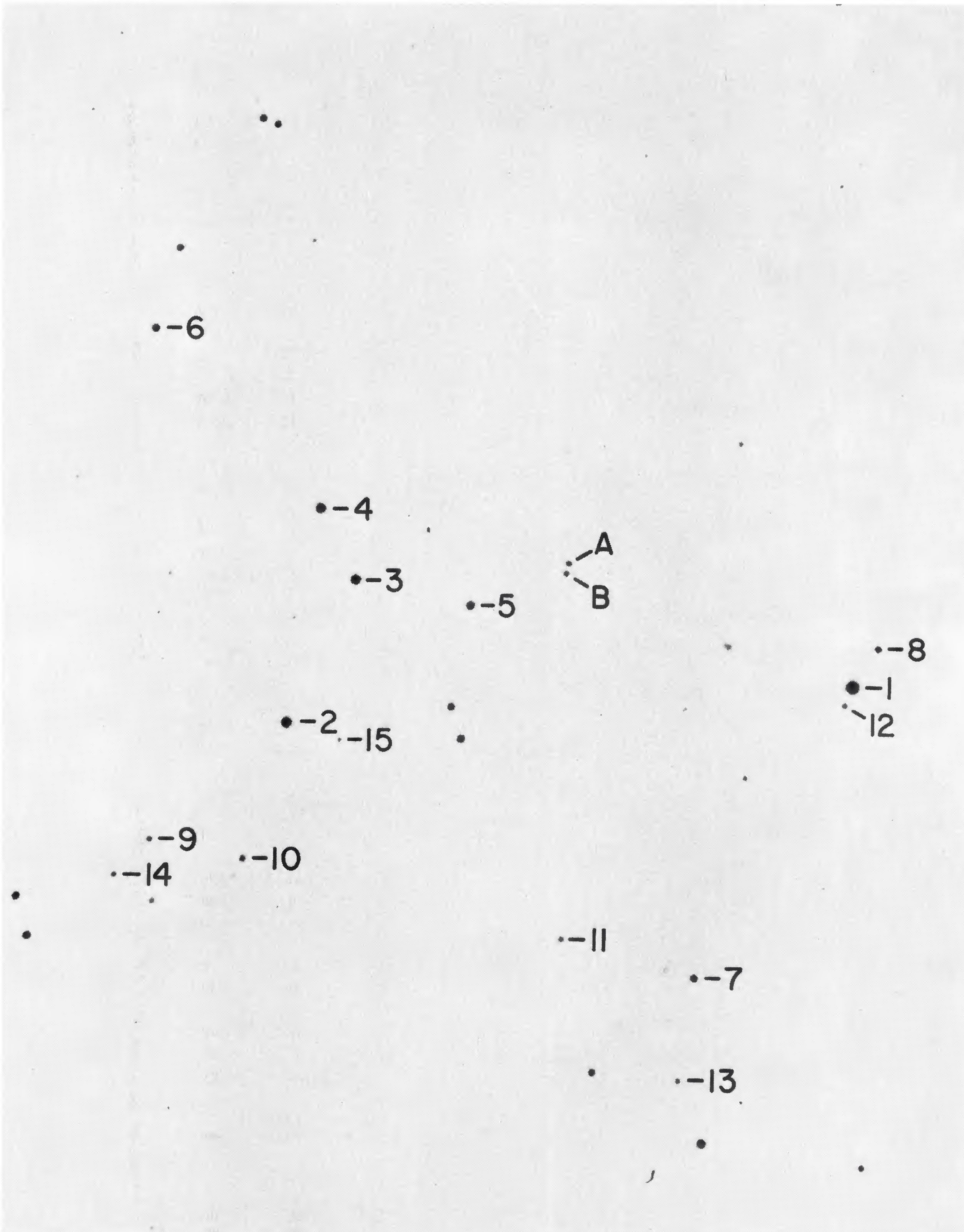

FIG. 1.—Photoelectric sequence stars from Table 1 marked on a reproduction of the 18 May 1980 Crossley plate. The QSO images are marked as A and B. North is at the top; the field is 10′.5 by 13′.0.

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