Winter 1-15-1989

OTS 1809+314 and the Gamma-Ray Burst GB 790325b

Dieter H. Hartmann
Department of Physics and Astronomy, Clemson University, hdieter@clemson.edu

Richard W. Pogge
Lick Observatory and Board of Studies in Astronomy and Astrophysics - University of California & Insitute of Geophysics and Plaentary Physics - University of California

Kevin Hurley
Space Sciences Laboratory, University of California, Berkeley

Frederick J. Vrba
US Naval Observatory, Flagstaff Station

Mark C. Jennings
Institute of Geophysics and Planetary Physics - Univeristy of California

Recommended Citation

Please use publisher's recommended citation.

The Astrophysical Journal, 336:889–895, 1989 January 15

OTS 1809+314 AND THE GAMMA-RAY BURST GB 790325b[1]

Dieter Hartmann and Richard W. Pogge
Lick Observatory and Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz; and Institute of Geophysics and Planetary Physics, University of California, Lawrence Livermore National Laboratory
Kevin Hurley
Space Sciences Laboratory, University of California, Berkeley; and Centre d'Etude, Spatiale des Rayonnements, Toulouse, France
Frederick J. Vrba
U.S. Naval Observatory, Flagstaff Station
and
Mark C. Jennings
Institute of Geophysics and Planetary Physics, University of California, Riverside
Received 1988 May 23; accepted 1988 July 6

ABSTRACT

We present deep CCD images of the field containing the recurring Optical Transient Source (OTS) 1809+314 recently discovered on archival plates of the Sonneberg Observatory. At the position of OTS 1809+314 we find no optical counterpart brighter than $V = 24.0$–24.5, $r_{\rm GUNN} = 22.0$–22.5, and $I = 22.0$–22.5. In the zero proper motion limit our observations place severe constraints on possible quiescent counterparts. There is no compelling evidence to suggest an association between the historical optical transient source and the γ-ray burst GB 790325b located $\sim 5'$ to the east of OTS 1809+314.

Subject headings: gamma rays: bursts — stars: variables

I. INTRODUCTION

Three optical flashes occurring on UT 1946 March 28, UT 1946 August 31, and UT 1954 April 27 at an identical location were recently discovered on archival plates of the Sonneberg Observatory (Hudec 1986; Hudec *et al.* 1989; see also Bignami 1987). The observations indicate that the optical flashes had durations of $\lesssim 1$ minutes, and reached magnitudes between ~ 4 and 6 in the photographic *B* band (assuming a flash duration of 1 s; Hudec *et al.* 1989). The repeated appearance of this source (henceforth designated OTS 1809+314) suggests that it is a true cosmic source. Satellite glints suggested as the cause (Maley 1987; Schaefer *et al.* 1987; Vanderspek, Zachary, and Ricker 1986; Tokarz *et al.* 1989) of the "Perseus Flasher" (Katz *et al.* 1986) cannot be responsible for these transients because *Sputnik I* was not launched until 1957 October 4. Plate faults or head-on meteors are also unlikely, as the probability for three events well separated in time occurring at the same position is negligible. Based on the observational properties of the Sonneberg plate collection (Hudec *et al.* 1987) we calculate a probability $P \sim 2 \times 10^{-7}$ for three false images inside our localization circle.

Hudec *et al.* (1989) have tentatively identified OTS 1809+314 as the optical counterpart of the "nearby" (separation of $\sim 5'$) γ-ray burst GB 790325b (Laros *et al.* 1985). This is justified in principle since optical flashes are believed to be associated with γ-ray bursts (Schaefer 1981; Schaefer *et al.* 1984; but see also Zytkow 1989; Pedersen *et al.* 1984; Moskalenko *et al.* 1989; see Hartmann and Woosley 1988 and references therein for a recent review of the observational and theoretical status of this conjecture). Indeed, the unambiguous demonstration of a causal connection between these two phenomena would have important implications for our understanding of the enigmatic γ-ray burst phenomenon. This question is discussed in detail in § III*a*. The observations, carried out at Lick Observatory and the U.S. Naval Observatory, Flagstaff Station, are presented in § II. In § III*b* we discuss constraints on possible quiescent counterparts of OTS 1809+314 assuming that the source has approximately zero proper motion. In § III*c* we briefly discuss the status of our ongoing long-term study of this region which could lead to the identification of a counterpart with nonnegligible proper motion.

II. OBSERVATIONS

Deep broad-band CCD images of the field containing the GB 790325b error box were obtained as part of an ongoing systematic study of well defined γ-ray burst error boxes at Lick Observatory and the U.S. Naval Observatory, Flagstaff Station. The proximity of the fifth magnitude star 104 Herculis to the GB 790325b error box required off-center exposures of this field, thus fortuitously including the field of OTS 1809+314.

The Lick Observatory CCD images were obtained on the night of UT 1986 May 12 with the 1 m Anna Nickel telescope at Mount Hamilton, California using the f/17 Cassegrain CCD

TABLE 1

Observation Log

Date	Telescope	Filter	Exposure (s)	Seeing
1986 May 12	40 inch Lick	*V*	360	1″.5
1986 May 12	40 inch Lick	*r*	360	1.4
1987 Jul 19	40 inch USNO	*V*	3600	2.0
1987 Jul 20	40 inch USNO	*I*	2400	2.3
1987 Sep 29	40 inch USNO	*I*	2700	2.0
1987 Sep 30	40 inch USNO	*V*	600	2.3
1987 Sep 30	40 inch USNO	*I*	600	2.1

---

[1] *Lick Observatory Bulletin*, No. 1114.

spectrograph in its direct imaging mode with a Texas Instruments 500 × 500 three-phase CCD detector. Two sets of exposures of 300 s and 60 s duration were made through a Johnson *V* band filter and a Gunn *r* band filter (Thuan and Gunn 1976) (Table 1). *UBVRI* standard star fields in M92 and NGC 4147 (Christian *et al.* 1985) were observed to provide an absolute flux calibration. The image analysis was done using the VISTA image processing package developed at Lick Observatory. The details of the basic image reduction techniques have been discussed earlier (Hartmann and Pogge 1987). For each filter, the 300 s and 60 s exposures were co-added to produce a single 360 s exposure.

The U.S. Naval Observatory CCD images were obtained on five nights between UT 1987 July 19 and UT 1987 September 30 with the 1 m telescope at Flagstaff Station using the Texas Instruments 800 × 800 CCD detector on loan to USNO from the Space Telescope Wide-Field Planetary Camera group (Westphal *et al.* 1982). Exposures of 60 and 10 minute duration were made through a F555W filter and exposures of 45, 40, and 10 minute duration were made through a F791W filter (Table 1). We used only the deepest *V* band and *I* band images in our analysis, but none of the other exposures showed anything inconsistent with these two frames.

Secondary photometric standards in the field were created by observing primary *UBVRI* photometric standard stars (Landolt 1983). The image analysis was done using a Gould De Anza picture processing system and image processing software written by David G. Monet at USNO. Photometry was performed using DAOPHOT (Stetson 1987).

The position of OTS 1809+314 on the CCD images was determined from relative astrometric measurements of print reproductions of the 1946 March 28 and 1946 August 31 plates (kindly provided by R. Hudec). Figure 1 shows the central 8′ × 4′ of a 60 s Gunn *r* CCD image. On the left (east), is the outline of the GB 790325b error box (Laros *et al.* 1985). The diagonal streaks are diffraction spikes from 104 Her. The location of OTS 1809+314 is shown as a 20″ diameter circle which represents a conservative estimate of the uncertainty of our relative coordinate transformation between the archival plate and our CCD image. The dashed region roughly indicates the boundary of the OTS 1809+314 field discussed below and shown in Figures 2 and 3.

A 4′ × 3′ region containing OTS 1809+314 in the 360 s Gunn *r* band is shown in Figure 2. We have determined the magnitudes of eight numbered field stars shown in Figure 2 using the photometric reduction routines in the VISTA package. The faintest stars in the field have $r_{\rm GUNN} = 21.4 \pm 0.8$ and $V = 20.8 \pm 0.4$ mag. Within the location circle of OTS 1809+314 there are no star-like or diffuse objects visible on either image. A 3 σ detection limit derived from the mean background level indicates that there are no point sources brighter than $r_{\rm GUNN} = 22.0$–22.5 mag and $V = 21.5$–22.0 mag inside the 20″ error circle.

A 3′ × 3′ region containing OTS 1809+314 in the 60 minute *V* band image is shown in Figure 3. We have determined the *V* band and *I* band magnitudes of ~100 stars in the field using DAOPHOT. The $V - I$ colors do not reveal any unusual objects (they range between ~0.5 and ~3.0). The faintest stars in the field have $V = 23.2 \pm 0.3$ and $I = 21.2 \pm 0.4$ mag. Within the location circle of OTS 1809+314 there are no star-

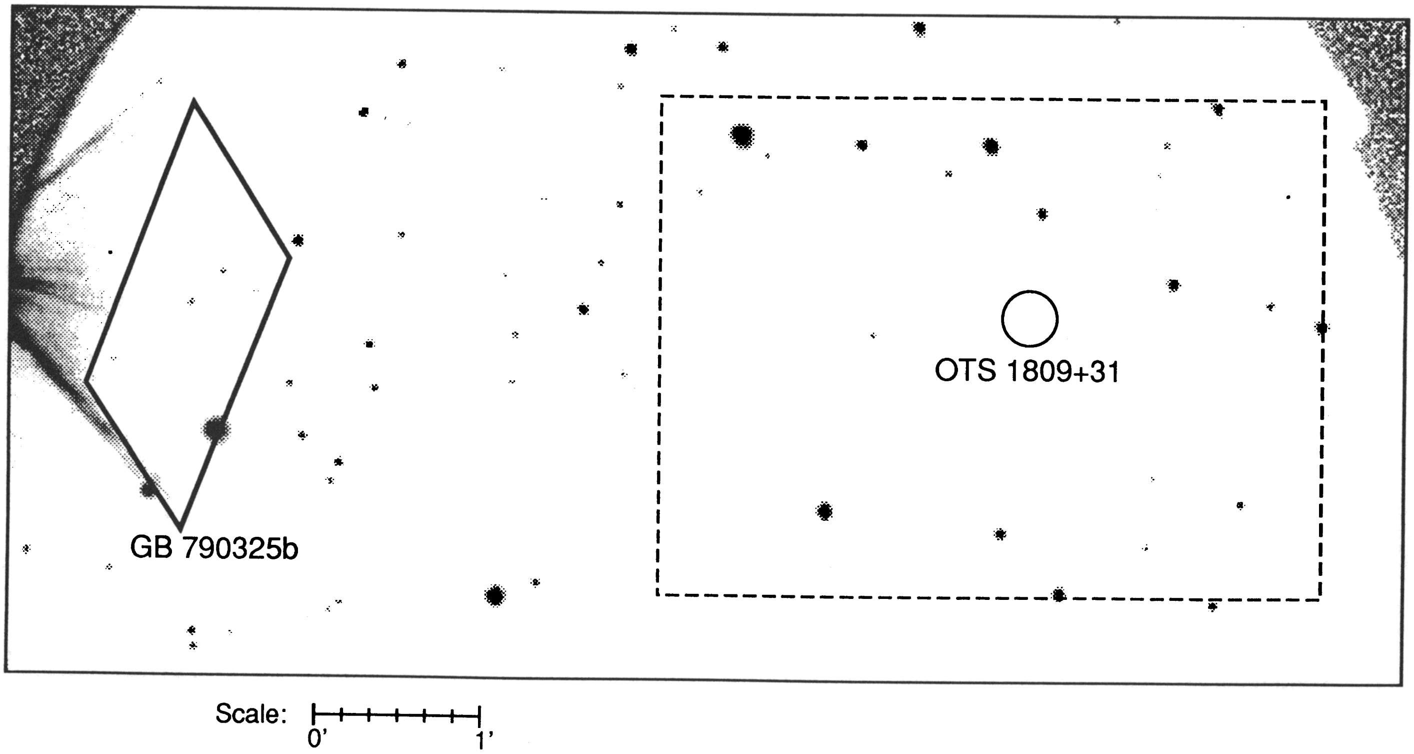

FIG. 1.—The central 8′ × 4′ of the 60 s Gunn *r*-band CCD image containing the field of the error box of the γ-ray burst GB 790325b and the repeating optical transient source OTS 1809+314. The diagonal streaks crossing the GB 790325b error box are diffraction spikes from 104 Her. In this image, north is up, east is to the left. The scale bar indicates the size of 1′ projected on the sky, with subdivisions every 10″. The position of OTS 1809+314 was determined by relative astrometry using print reproductions kindly supplied by R. Hudec.

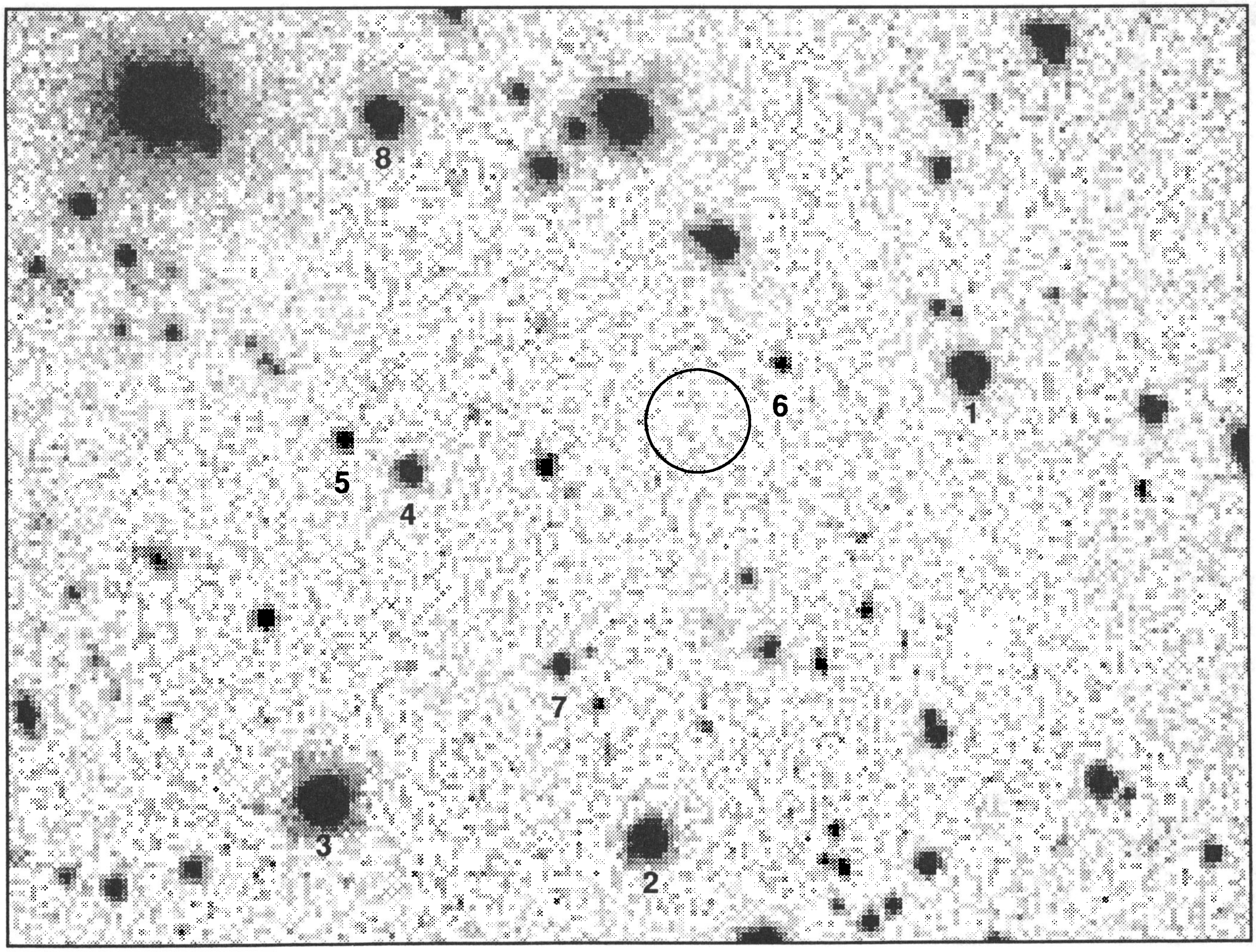

FIG. 2.—360 s Gunn r-band CCD image of the 4′ × 3′ field surrounding OTS 1809+314. The location of OTS 1809+314 is within the 20″ circle. No point sources brighter than $r_{\mathrm{GUNN}} = 22$–22.5 mag in the appear within the location circle of OTS 1809+314. The orientation is north up, east to the left.

like or diffuse objects visible on either image. A 3 σ detection limit derived from the mean background level indicates that there are no point sources brighter than $V = 24.0$–24.5 mag and $I = 22.0$–22.5 mag inside the 20″ error circle. The two objects nearest to the error circle have magnitudes of $V = 21.7 \pm 0.1$, $I = 20.0 \pm 0.2$ (NW star) and $V = 22.1 \pm 0.1$, $I = 20.3 \pm 0.2$ (SE star) and colors $V - I \sim 1.7$ typical for main-sequence stars of spectral type K-M (Allen 1973). Additional information on these potential counterpart candidates (e.g., spectra) would be desirable, but it would require many hours of large aperture telescope time to obtain good signal-to-noise spectra at these magnitudes.

III. DISCUSSION

The interpretation of our observations separates naturally into three parts. First, we consider the suggested identification of OTS 1809+314 as the optical counterpart of GB 790325b (Hudec 1986; Hudec *et al.* 1989). No deep CCD images are necessary to address this important question. We present our arguments against the proposed association in § III*a*. In order to place constraints on a possible optical counterpart of OTS 1809+314 we need to consider the possibility of substantial proper motion of the source over the period of 40 yr since the observed optical outbursts. If we assume negligible proper motion, our observations severely constrain the quiescent optical properties of the counterpart (§ III*b*). If we abandon the restrictive assumption of negligible proper motion we can use the recurrent nature of OTS 1809+314 to place stringent limits on the proper motion. However, the quality of the archival plate material still leaves us with a very large error box in which to search for a possible counterpart. In § III*c* we discuss our approach to this "needle in the haystack" problem.

a) The Relationship between OTS 1809+314 and GB 790325b

Evidence for historical transient optical flashes within contemporary γ-ray burst error boxes was first reported by Schaefer (1981) and Schaefer *et al.* (1984) who searched the Harvard archival plate collection. However, serious doubts about the reality of these optical transients were raised in a recent reexamination of this plate material (Zytkow 1989). Similar work utilizing plate collections of several other observatories has resulted in the detection of a few additional optical flash sources (Moskalenko *et al.* 1989; Greiner *et al.* 1989). Although

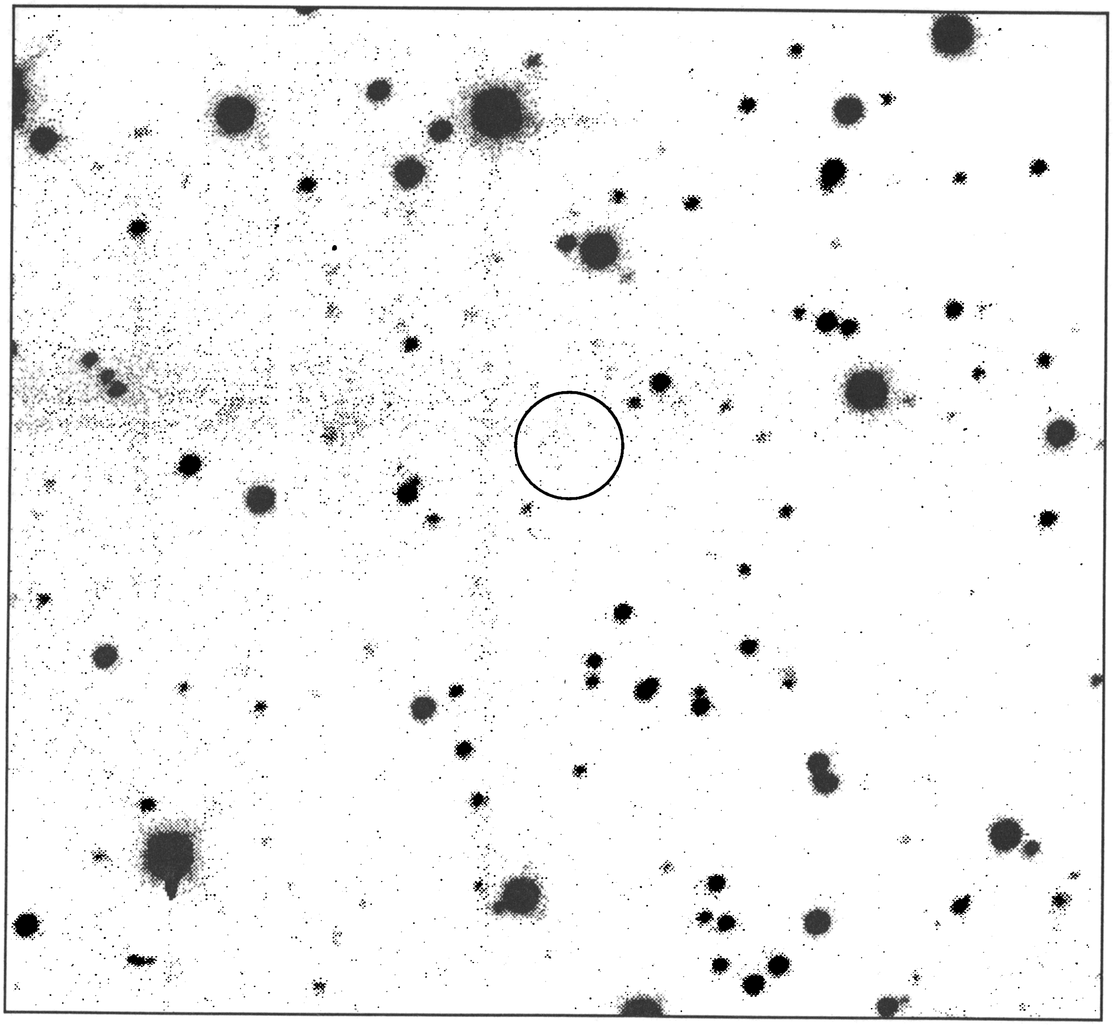

FIG. 3.—Sixty minute V-band CCD image of the 3′ × 3′ field surrounding OTS 1809+314. The location of OTS 1809+314 is within the 20″ circle. No point sources brighter than $V = 24.0$–24.5 mag in the appear within the location circle of OTS 1809+314. The orientation is north up, east to the left.

unconfirmed, the detection of several transient optical events from direct photoelectric monitoring of well localized γ-ray bursts (Pedersen *et al.* 1984; Hurley 1987; R. Schwartz *et al.* 1988, private communication) provides additional support to the conjecture that brief "optical" flashes are associated with γ-ray bursts. Long-wavelength emission from γ-ray bursts is expected at some level according to a number of models (London 1984; Cominsky, London, and Klein 1987; Rappaport and Joss 1985; Melia, Rappaport, and Joss 1986; Melia 1988*a*, *b*; Epstein 1985; Woosley 1984; Hartmann, Woosley and Arons 1987, 1988). An important quantity for the theoretical understanding of optical flashes from γ-ray bursts is the ratio of energy emitted above ~30 keV to that emitted into the optical band, $R_{\gamma 0}$. Although the lack of truly simultaneous γ-ray/optical data introduces large uncertainties in the estimate of this number, the above mentioned observations lead to estimates of $R_{\gamma 0}$ between 10^3 and 10^4. Based on the γ-ray data for GB 790325b (Laros *et al.* 1985), Hudec *et al.* (1989) estimate that $R_{\gamma 0}$ could be as small as ~300 for the main outbursts of OTS 1809+314. Such a high γ-ray to optical conversion efficiency lies far beyond the observationally suggested values for $R_{\gamma 0}$ and, if correct, requires emission mechanisms that are more efficient than those invoked in the models proposed to date. It is important to address the question of the causal connection between the optical transients and the γ-ray burst source.

In the case of OTS 1809+314 it is unlikely that the γ-ray bursts of 1979 could have originated from the same object that caused the three optical flashes. The necessary EW proper motion ($\sim 10''$ yr^{-1}) is comparable to the largest proper motions known (e.g., Allen 1973). However, the three optical events were separated by ~8 yr so that one can derive upper limits on the proper motion from the fact that to within the measurement errors all events occurred at the same location. Based on the appearance of the archival plate images, R. Hudec (1987, private communication), has derived a very conservative upper limit of 2″.5 yr^{-1} in EW direction and 5″ yr^{-1} NS. These limits reflect the poor image quality of the third plate (UT 1954 April 27 event), which was obtained with a different camera from that of the first two events. Such a large NS proper motion would have been easily detected between the UT 1946 March 28 and UT 1946 August 31 events. Our measurements of the corresponding prints place the maximum allowed total proper motion at $\lesssim 2''$ yr^{-1}. Yet, even Hudec's large limits on the proper motion of OTS 1809+314 are insufficient to move it into the γ-ray burst error box.

To surmount this apparent discrepancy, Bignami (1987) considered inaccuracies in the γ-ray burst source localization. However, modifications of the ($\sim 3\ \sigma$) error box (Laros *et al.* 1985; see also Fig. 1) involving more than a fraction of its own size would require the conspiracy of several previously unnoticed systematic effects (Laros 1988). Thus a separation of several arcminutes implies a vanishing probability of OTS 1809+314 being associated with GB 790325b. We conclude that it is extremely unlikely that OTS 1809+314 and GB 790325b are related, making the previously reported value of $R_{\gamma 0}$ (Hudec *et al.* 1989) problematic.

b) *Zero Proper Motion Constraints*

Independent of its association with γ-ray bursts, this transient source is an interesting and curious *optical* phenomenon. Hudec *et al.* (1989) have estimated that the optical transients were brief ($\lesssim 1$ minute duration) and perhaps between fourth and sixth magnitude in brightness. If we assume that the counterpart of OTS 1809+314 has negligible proper motion, the deep CCD images presented in § II place severe constraints on the quiescent counterpart as well as on possible generation mechanisms for the optical outbursts. Since we see no sources in our error circle brighter than $m_V = 24$ mag, this may imply an increase in brightness of $\gtrsim 10^8$ in $\lesssim 1$ minute. Such large excursions in brightness can be achieved in supernovae explosions (e.g., the shock break-out spike from SN 1987*a*; Woosley, Pinto, and Ensman 1988), but supernovae fade in brightness over much longer time scales. No known class of recurring eruptive variables has been observed to increase in brightness by such a large factor in so short a time (Hoffmeister, Richter, and Wenzel 1985).

Assuming zero proper motion we use the measured magnitude limits to obtain lower distance limits to a variety of well known astronomical objects (Table 2). We correct for extinction using $A_V = 3E(B-V)$ (Whitford 1958) with a reddening of $E(B-V) \sim 0.06$ taken from the compilation of Burstein and Heiles (1982). From the galactic latitude of OTS 1809+314 ($b \sim 22°$) we then obtain the ratio, β, of the corresponding height of the object above the galactic plane to the scale height of its class (Table 2). Objects with $\beta \gg 1$ are essentially ruled out as possible zero proper motion counterparts.

Although we believe that OTS 1809+314 is not related to GB 790325b, it is possibly related to another, as yet undetected, γ-ray burst source. The number of such sources in our galaxy is unknown, since it depends on the unknown γ-ray burst recurrence time scale. But reasonable estimates for this time scale lead to probabilities in the range 10^{-3}–1 that an unknown γ-ray burst source could be in the 20″ diameter error circle. Since it is commonly, but not universally, believed that the "canonical" γ-ray burst counterpart should involve a neutron star (e.g., Woosley 1984; Lamb 1984; Liang and Petrosian 1986; Taam 1987; Hartmann and Woosley 1988) we consider a "hot" ($T = 10^6$ K) and a "cold" ($T = 10^5$ K) neutron star as potential candidates. If the quiescent counterpart of OTS 1809+314 is still inside our localization error circle, the optical constraints derived in this work demand distances exceeding 10 pc, even if we assume a lone neutron star old enough to have cooled to $\sim 10^5$ K (Table 2). The distance limits are derived assuming a blackbody spectrum, a stellar radius $R = 10$ km and neglecting redshift corrections. Both the neutron star radius and the redshift factor, z, depend sensitively on the equation of state at high density ($\rho = 0.1$–1.0 fm^{-3}). Recent microscopic calculations of the equation of state (Wiringa, Fiks, and Fabrocini 1988) taken together with constraints on the mass-radius relation from observations of the X-ray burst source MXB 1636−536 (Fujimoto and Taam 1986) appear to rule out very stiff equations of state that allow radii much in excess of 10 km. Very soft equations of state that could give radii much smaller than 10 km are excluded because they cannot accommodate the observed neutron star mass $M = 1.85 \pm 0.35\ M_\odot$ in the X-ray binary system 4U0900−40 (Joss and Rappaport 1984; see also Glendenning 1989). Estimates of the redshift factor obtained from emission features around 400 keV observed in a number of γ-ray burst spectra (interpreted as redshifted electron-positron annihilation radiation) range between 0.25 and 0.35 (Lindblom 1984; Liang 1986). Larger radii and substantial redshifts increase the neutron star brightness according to

$$M_V \sim 23.5 - 5\log_{10}\left(\frac{R}{10\ \mathrm{km}}\right) - 2.5\log_{10}\left(\frac{T}{10^5\ \mathrm{K}}\right) - 5\log_{10}(1+z)\,,$$

where we have used the Rayleigh-Jeans law, which yields somewhat larger distance limits.

c) *Search for the Counterpart*

If we allow for non-negligible proper motion of the counterpart we obviously face the classical "needle in the haystack" problem. Although our proper motion upper limits are very

TABLE 2

OTS 1809+314 ZERO PROPER MOTION DISTANCE LIMITS[a]

Object Class	Typical M_V	Nearest Member (pc)	Distance Limit (pc)	β[b]
Star O5V	−6	1000	1×10^7	2×10^5
Star G0V	4.5	10	7.3×10^4	200
Star M0V	9	1	9.2×10^3	30
Bright white dwarf	10	10	5.8×10^3	10
Faint white dwarf	15	10	580	1
Star M8V	16	1	360	1
Neutron star (10^6 K)	21	400[c]	40	0.4[c]
Neutron star (10^5 K)	23.5	30[d]	13	0.01[d]

[a] Estimates are based on the magnitude limit $m_V \geq 24$.

[b] Except for neutron stars the scale heights are taken from Allen 1973.

[c] We assume 10^3 neutron stars in an exponential disk with scale height 100 pc.

[d] We assume 10^8 neutron stars in an exponential disk with scale height 1 kpc.

conservative, we are still left with a search area of $\sim 1' \times 1'$. Since we do not know *a priori* what a γ-ray burst source looks like in quiescence, we might search for objects with "peculiar" properties inside the search area, although we do not have any reason to assume that the quiescent counterpart should be unusual in any way. Criteria for "peculiarity" might include variability, unusually large proper motion, strong polarization, detectable X-ray flux, unusual color, morphological appearance, or spectral properties. The $V - I$ color distribution of the ~ 100 stars in a $3' \times 3'$ field surrounding OTS 1809+314 (ranging between ~ 0.5 and ~ 3.0) does not reveal any object with an extreme color (see also Ricker *et al.* 1989). However, even if one of the above criteria is satisfied we are still far from an unambiguous identification of the counterpart. Besides obtaining potential counterpart candidates, what would we learn from the detection of an object of extreme color or high degree of polarization somewhere in the search area? The best we can do to support an assumed association is to determine the proper motion of that object. Examination of an area within $\sim 6'$ around OTS 1809+314 on the plates of the Lick Observatory proper motion survey (Klemola, Jones, and Hanson 1987) reveals no object with proper motion in excess of $0''.2$ yr^{-1} down to the limiting blue magnitude of ~ 19 (A. R. Klemola 1987, private communication). To obtain sensible proper motion estimates down to the detection limit of our CCD images requires a much larger time base than available at present. The systematic search for proper motion objects inside γ-ray burst error boxes is one of the main objectives of our ongoing USNO monitoring program. A meaningful estimate of the proper motion in the OTS 1809+314 field requires multiple CCD images obtained over a baseline of at least three or more years and will be the subject of a forthcoming paper.

Meanwhile, multiwavelengths surveys of the region surrounding OTS 1809+314 should be performed to determine possible candidates for the quiescent counterpart. Recent X-ray observations utilizing the *EXOSAT* Channel Multiplier Array have not resulted in a statistically significant detection of an X-ray point source down to an energy flux limit of $\sim 10^{-13}$–10^{-12} ergs cm^{-2} s^{-1} (Boer *et al.* 1989). These observations imply a lower limit on the distance to a neutron star in the general field of OTS 1809+314 of ~ 5 kpc for $T \sim 10^6$ K, and ~ 50 pc for $T \sim 10^5$ K.

Finally, if one of the objects in the general field around OTS 1809+314 is responsible for the optical outbursts, the brightening increase of the counterpart might be much less extreme than that obtained in the zero proper motion limit above. Indeed, Ricker *et al.* (1989) considered a flare star origin for the outbursts based on the detection of a large number of stars with $m_R \sim 18.5$–22.5 near their optical error box (note that their error box does not coincide with our localization, although that has no consequences in this context). However, we feel that a meaningful interpretation of the optical phenomenon discovered by Hudec *et al.* must await an unambiguous identification of the counterpart. Finding the proverbial "smoking gun" is a formidable task and our ongoing long-term systematic photometric and proper motion survey of the OTS 1809+314 field appears to be the most promising approach to this problem.

We are grateful to R. Epstein, B. Jones, A. Klemola, J. Laros, W. Priedhorsky, and S. Woosley for encouragement and many helpful discussions and to R. Hudec for generously furnishing his data and unpublished results. We are also grateful to Jim Westphal for lending the 800 × 800 TI CCD of the Wide-Field Planetary Camera development group to USNO. This research has been supported by the Cal Space Institute under grants CS-69-85, and CS-79-87 and CS-32-88, the Institute of Geophysics and Planetary Physics at the Los Alamos National Laboratory (Project Nos. 138 and 142), the Institute of Geophysics and Planetary Physics at the Lawrence Livermore Laboratory (UCLA-LLL-IGPP-PC 831003), by the NSF under grant AST 84-18185, by the UCSC Davidson Fund, and the NASA Grant NGR 05-008-022. CCD instrumentation and VISTA software development at Lick Observatory were funded in part by NSF Core Block Grant AST 86-14510.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (London: Athlone).
Bignami, G. F. 1987, *Nature*, **330**, 316.
Boer, M., *et al.* 1989, *Astr. Ap.*, in press.
Burstein, D., and Heiles, C. 1982, *A.J.*, **87**, 1165.
Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R., and Siegel, M. 1985, *Pub. A.S.P.*, **97**, 363.
Cominsky, L. R., London, R. A., and Klein, R. I. 1987, *Ap. J.*, **315**, 162.
Epstein, R. I. 1985, *Ap. J.*, **291**, 822.
Fujimoto, M. Y., and Taam, R. E. 1986, *Ap. J.*, **305**, 246.
Glendenning, N. K. 1989, *Phys. Rev. C*, in press.
Greiner, J., Flohrer, J., Wenzel, W., and Lehmann, T. 1989, *Adv. Space Res.*, submitted.
Hartmann, D., and Pogge, R. W. 1987, *Ap. J.*, **318**, 363.
Hartmann, D., and Woosley, S. E. 1988, in *Multi-Wavelength Astrophysics*, ed. F. Córdova (Cambridge: Cambridge University Press), p. 189.
Hartmann, D., Woosley, S. E., and Arons, J. 1987, *Bull. AAS*, **18**, 928.
———. 1988, *Ap. J.*, **332**, 777.
Hoffmeister, C., Richter, G., and Wenzel, W. 1985, *Variable Stars* (Berlin-Heidelberg: Springer-Verlag).
Hudec, R. 1986, *Inf. Bull. Var. Stars*, **2948**.
Hudec, R., *et al.* 1987, *Astr. Ap.*, **175**, 71.
Hudec, R., Borovicka, J., Danis, S., Franc, V., Peresty, R., and Vanicek, B. 1989, *Adv. Space Res.*, submitted.
Hurley, K. 1987, *Ap. Letters*, **25**, 145.
Joss, P. C., and Rappaport, S. A. 1984, *Ann. Rev. Astr. Ap.*, **22**, 537.
Katz, B., *et al.* 1986, *Ap. J.* (*Letters*), **307**, L33.
Klemola, A. R., Jones, B. F., and Hanson, R. B. 1987, *A.J.*, **94**, 501.
Lamb, D. Q. 1984, *Ann. NY Acad. Sci.*, **422**, 237.
Landolt, A. U. 1983, *A.J.*, **88**, 439.
Laros, J. G. 1988, *Nature*, **333**, 124.
Laros, J. G., *et al.* 1985, *Ap. J.*, **290**, 728.
Liang, E. P. 1986, *Ap. J.*, **304**, 682.
Liang, E. P., and Petrosian, V. 1986, *AIP Conf. Proc. 141*, *Gamma-Ray Bursts*, ed. E. P. Liang and V. Petrosian (New York: AIP).
Lindblom, L. 1984, *Ap. J.*, **278**, 364.
London, R. A. 1984, *AIP Conf. Proc. 115*, *High-Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 581.
Maley, P. D. 1987, *Ap. J.* (*Letters*), **317**, L39.
Melia, F. 1988*a*, *Ap. J.* (*Letters*), **324**, L21.
———. 1988*b*, *Ap. J.*, in press.
Melia, F., Rappaport, S., and Joss, P. C. 1986, *Ap. J.* (*Letters*), **305**, L51.
Moskalenko, E. I., *et al.* 1989, *Adv. Space Res.*, submitted.
Pedersen, H., *et al.* 1984, *Nature*, **312**, 46.
Rappaport, S. A., and Joss, P. C. 1985, *Nature*, **314**, 242.
Ricker, G. R., Mock, P. C., Ajhar, E. A., and Vanderspek, R. K. 1989, *Ap. J.*, in press.
Schaefer, B. E. 1981, *Nature*, **294**, 722.
Schaefer, B. E., *et al.* 1984, *Ap. J.* (*Letters*), **286**, L1.
———. 1987, *Ap. J.*, **320**, 398.
Stetson, P. B. 1987, *Pub. A.S.P.*, **99**, 191.
Taam, R. E. 1987, in *Proc. 13th Texas Symposium on Relativistic Astrophysics*, (Chicago), ed. M. P. Ulmer (Singapore: World Scientific), p. 546.
Thuan, T. X., and Gunn, J. E. 1976, *Pub. A.S.P.*, **88**, 543.
Tokarz, S., Browne, S., Klemola, A. R., McCrosky, R., Kulkarni, S. K., and Djorgovski, S. 1989, *Pub. A.S.P.*, in press.
Vanderspek, R. K., Zachary, D. S., and Ricker, G. R. 1986, *Adv. Space Res.*, **6**, (No. 4), 69.
Westphal, J. A., *et al.* 1982, in *Proc. IAU Commission 44*, *The Space Telescope Observatory*, (Patras, Greece), ed. D. N. B. Hall (Baltimore: Space Telescope Science Institute), p. 28.

Whitford, A. E. 1958, *A.J.*, **63**, 201.
Wiringa, R. B., Fiks, V., and Fabrocini, A. 1988, preprint.
Woosley, S. E. 1984, in *AIP Conf. Proc. 115, High-Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 485.
Woosley, S. E., Pinto, P., and Ensman, L. 1988, *Ap. J.*, **324**, 466.
Zytkow, A. N. 1989, *Ap. J.*, submitted.

DIETER HARTMANN: Board of Studies in Astronomy and Astrophysics, University of California at Santa Cruz, CA 95064

KEVIN HURLEY: University of California at Berkeley, Space Sciences Laboratory, Berkeley, CA 94720

MARK C. JENNINGS: Institute of Geophysics and Planetary Physics, University of California, Riverside, CA 92521

RICHARD W. POGGE: McDonald Observatory, The University of Texas at Austin, RLM 15.308, Austin, TX 78712

FREDERIC J. VRBA: U.S. Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002