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TWO PROBABLE OPTICAL FLASHES FROM GAMMA-RAY BURSTERS[1]

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ABSTRACT

We have located two images on archival photographic plates which are most likely records of optical flashes from gamma-ray bursters (GRBs). One of these images appears on a 1901 plate in the field of the 5 November 1979 GRB, while the other is in the field of the 13 January 1979 GRB on a plate exposed in 1944. The 1901 optical transient image is circular in shape, while all normal star images are trailed by 8". No optical transients are found in a control region which is 34.3 times larger than the GRB error regions examined. Independent limits on the optical flash rate from the sky yield a probability of less than 10^{-4} that any one of the optical transients is due to a background flash. A total exposure of 2.7 years has been examined for GRB flashes at known GRB locations on the Harvard plates and a total of three GRB flashes have now been seen which implies that the average recurrence time scale for optical flashes is roughly one year. The optical fluence of these optical flashes has been measured. For the three currently known GRB optical flashes, the ratio of gamma-ray fluence (from a moderr burst) to the optical fluence (from a archival burst) were measured to be 800, 900, and 900.

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I INTRODUCTION

Since the gamma-ray burster (GRB) phenomenon was first announced in 1973 (Klebesadel, Strong, and Olson 1973), the identification of low-energy counterparts has been a primary goal of GRB research. In general, no quiescent counterparts have been convincingly identified (Hurley 1983). Schaefer (1981) reported the probable identification of a bursting counterpart. The counterpart appeared as a "new" star image on an archival photographic plate exposed in 1928. The image appeared inside both the gamma-ray and x-ray error boxes associated with the 19 Nov 1978 GRB (Cline et al. 1981 and Grindlay et al. 1982). The position on the sky of the transient was empty on plates taken both 45 minutes before and after. The 1928 transient image was distorted due to coma from the telescope and yet was not trailed while all other images on the plate were trailed by 17". If the 1928 flash had a constant brightness during outburst and a duration of one second, then its apparent magnitude would have been 3.3 magnitude. The total optical energy emitted by the 1928 flash was 800 times smaller than the total gamma-ray energy emitted during the 1978 burst.

The sum of the exposure for all plates examined in the first Harvard plate search was 0.5 years. Three GRB regions were examined and one bursting counterpart was identified. This suggests that GRBs have a short recurrence time and that an extension of the search to additional GRB error regions could uncover more GRB optical flashes. This extended search has now been made possible by the localization of seven GRBs (Cline et al. 1983 and Barat et al. 1983). These regions have been examined on the Harvard plates with a total cumulative exposure of 2.7 years. This paper reports the identification of two more optical transients probably associated with gamma-ray bursters (for a total of three known transients).

II 1901 OPTICAL TRANSIENT

On one of the plates which show the 5 Nov 1979 GRB field (Cline et al. 1983) a "new" 13.7 magnitude star appears in the gamma-ray error box (see

Figure I). The plate is B28642, an eleven minute blue exposure reaching to $14^{m}.2$ taken on 4 Oct 1901. This "new" star was not seen on several plates from the same night which had a limiting magnitude of only 12^{m}. Plates exposed both a month before and after the "new" star show that at those times it was not brighter than 16^{m}. No other "new" star at this or any other location near the 5 Nov 1979 GRB field was found on any other Harvard plate.

All normal star images on plate B28642 are trailed by 8". The image of the 1901 optical transient is circular (the FWHM is 63 μm ± 5 μm in both right ascension and declination). The FWHM of normal star images is 90 μm ± 5 μm and 61 μm ± 5 μm in right ascension and declination respectively. The lack of trailing implies that the flash's duration was less than a few minutes.

The transient's image is located too close to the telescope's optical axis for any appreciable asymmetry due to coma to be present.

A short duration flash can have a much shallower profile (cf. Schaefer 1981), but this is not the only possible case as the degree of flattening depends critically on the flash duration and the individual plate's reciprocity failure. The faintness of the 1901 transient image ($0^{m}.5$ above the plate limit) and the plate scale (179"/mm) combine to make the transient image quite small (0.040 μm FWHM). Hence, it is not possible to measure accurately the slope of the transient's profile. However, the profile of the transient image and a comparison star were measured. The slope of the normal star's profile is steeper than the slope of the transient's profile, however the scatter in the profile data is large enough that this conclusion is not firm.

The position of the image was measured with a Mann measuring engine to be at $22^{h}51^{m}37^{s}.8 \pm 0^{s}.9$ and $-2^{\circ}31'32''.0 \pm 9''.0$ (1950). The error estimates correspond to a three sigma confidence level. The 1901 optical error box is empty on both red and blue plates from the Palomar Sky Survey.

What is the instantaneous magnitude of the 1901 optical flash if its duration was one second? The number of developed grains of the flash image appears to be equal to the number of developed grains of a trailed $13^{m}.7$

comparison star. Since the comparison star is trailed, its total number of developed grains will be different from than if it had been untrailed. Schaefer (1983) has quantitatively accounted for both this effect and the effect of reciprocity failure in the emulsion. (This correction must also be applied to the 1928 flash.) If the 1901 optical transient had a duration of one second, it would have reached a magnitude of $6^{m}.6$. On the assumption that the optical energy from the 1901 flash is equal to the optical energy from the 5 Nov 1979 GRB, $E_{\gamma}(>30\text{keV})/E_{opt}(\text{B band})$ is 900.

III 1944 OPTICAL TRANSIENT

A third "new" star image was found on a 1944 archival plate. The other "new" star is located in the 13 Jan 1979 GRB field (Barat et al. 1983). This object does not appear on plates exposed 5 days earlier nor 2 days later nor on any other plate in the Harvard collection. The "new" star image is on plate AM23468, a 90min blue exposure on 19 Feb 1944 from South Africa. It appears as a $12^{m}.1$ star when compared to nearby normal stars. The relevant area of plate AM23468 and a comparison plate is shown in Figure II.

The characteristics of the plate AM23468 do not lend themselves to providing evidence for the flash nature of an image. No other Harvard plates are available from the same night. The plate is not obviously trailed. The plate scale (600"/mm) is such that the image size (69 μm FWHM) does not allow for accurate analyses of the image shape or profile. The image appears so close to the plate center that effects due to coma are slight.

A microdensitometry study of the transient image was carried out, but the results are inconclusive due to the small size of the image. The measured slope of the transient's profile is roughly equal to that of a comparison star, although it appears to be consistently shallower. The scatter in the profile data does not allow for this to be a firm conclusion.

The position of the 1944 transient is $16^{h}31^{m}10^{s}.7 \pm 2^{s}.1$ and $-76^{\circ}30'52''.5 \pm 7''.5$ (1950). The quoted errors are for the three sigma level of confidence. The 1944 optical error box is also empty on the ESO Sky Survey glass plate.

On the assumption that the 1944 optical transient had a one second duration, the flash must have reached a magnitude of $4^{m}.3$. This translates into $E_{\gamma}(>30keV)/E_{opt}(B\ band) = 900$.

IV DISCUSSION

The properties of the three known optical transients are compared and summarized in Table 1. The lack of trailing of the 1901 transient image provides a strong argument for the GRB origin of the image. Perhaps the strongest argument for the transients' GRB origin comes from their proximity to known GRB positions.

As a control, several fields with no known GRB were examined on the Harvard plates. The coverage (in hour-steradians) of areas with no known GRB is 34.3 times the coverage of areas which contain a known GRB. No optical transients were found in the control region. Three optical transients were found in the GRB error regions The probability that all three optical transients are unrelated to the GRB phenomenon is therefore less than $2x10^{-5}$.

Currently available limits on the rate of flashes in the sky indicate that the observed optical transients are not likely to be from some background flash source. A search for flashes by K. Hurley and collaborators (1983 private communication) shows that the number of background flashes roughly as bright as the transients must be less than 0.017 per hour per steradian. A total of 0.004 hr-sr was examined on the Harvard plates which could have detected these flashes, and three flashes were found. Hence, the probability of any one of the transients being a background flash is less than $7x10^{-5}$. The probability that all three transients are from some background source is less than $3x10^{-13}$.

The positive evidence from the plates, the lack of negative evidence, the statistical arguments, and the lack of viable alternative explanations combine to provide strong support for the hypothesis that the transient images were caused by flashes from GRBs.

For the three observed cases of optical flashes from GRBs, the ratios

E_γ/E_{opt} were found to be 800, 900, and 900 (while E_γ varies by a factor of 25). Grindlay, Wright, and McCrosky (1974) found that E_γ/E_{opt}(V band) was greater than 800 for two GRBs. With only a small number of observed ratios, it is possible that the small scatter is coincidence. Indeed, the scatter in the observations is smaller than the estimated error bars for a single observation (±200). Also there are many potential sources of systematic errors. For example, the E_γ measurements from Mazets et al. (1981) are suspected to contain systematic errors (Laros et al. 1982). Despite these reservations, a tentative conclusion that the observed ratio E_γ(burst 1)/E_{opt}(burst 2) is roughly constant seems reasonable.

If the observed ratio should prove to be a constant, then that implies that (1) E_γ/E_{opt} is constant from GRB to GRB and from burst to burst, and (2) E_γ is a constant from burst to burst for a given GRB. The first condition is violated if the radiation pattern of gamma-ray or optical radiation is non-spherical or time varying. This could be used as an argument against the source of the optical flash being the reprocessing of gamma radiation on a companion star or accretion disc. The first condition would be satisfied if the geometry of the system is spherically symretric (eg. if the radiation is emitted from the whole surface of the neutron star or from some surrounding cloud) or if both the gamma and optical radiation are emitted from a region near the neutron star's axis of rotation.

Several GRB models have difficulty explaining the possibly constant E_γ. For example, in the asteroid collision model, E_γ will be proportional to the asteroid mass. Asteroid masses are likely to be distributed according to some power law. There will be two effects operating which will tend to select bursts with E_γ values within some range. Bursts with a low value of E_γ will not be observed on the Harvard plates, while bursts with high E_γ values will be rare. The selection probability for the Harvard plate search can be determined from the exposures and sensitivities of the plates. If the asteroid masses are assumed to follow a power law similar to the asteroids in the Solar System, the observed luminosity function for a given GRB can be determined. This distribution has a FWHM of two orders of magnitude. So it is likely that two bursts will have E_γ values which differ by over an order of magnitude. Under this circumstance, it would be coincidence if the three measured ratios had little scatter. Similar arguments can be made against many GRB models which use energy from the neutron star's interior. The thermonuclear flash model (Woosley 1982) could provide a simple explanation of why E_γ is constant because the flash will occur only when some critical amount of matter has accumulated so that a fixed amount of energy will be available.

With the finding of three GRB optical flashes in 2.7 years of observation, the average recurrence time scale for optical flashes must be approximately one year.

It is currently unclear whether this optical recurrence time scale is consistent with the gamma-ray recurrence time scale. Two GRBs have been observed to recur in gamma radiation on a time scale of months (Mazets, Golenetskii, and Gur'yan 1979 and Golenetskii et al. 1983) with several more possible cases of recurrence in the Konus data of Mazets et al. (1981). One of these is the anomalous 5 March 1979 event, which is thought by some to not be a "classical" GRB because of its many exceptional properties. We might expect more cases of recurrence in the decade of GRB observations if the E_γ for a given burster is roughly constant (as suggested above). Unfortunately, the fraction of observed GRBs with measured positions is low, especially for the Vela data. The Vela positional data are highly inhomogenous due to their requirement of other satellite data for an accurate position to be measured (which is neccesary to establish a case for recurrence). We have calculated a simple Monte Carlo model for this data set which shows it to be not inconsistent with a recurrence time scale of one year. The Konus data (Mazets et al. 1981) can not be readily used to check for the consistency of the observed recurrence time scale with a narrow luminosity function, because the observations have a duration comparable to the GRB recurrence time scale and the positional data only covers half the sky at a given moment (Mazets and Golenetskii 1982).

Should the two recurrence time scales prove to be different, a possible reason may be that E_γ varies from burst to burst (in contradiction to the suggestion above). In this case, the satellites would only detect and position the rare bright bursts. The faint bursts, if detected, would not be positioned and so no recurrence will be reported. Another possibility (suggested by W. Lewin) is that two separate classes of outbursts occur on GRBs; a rare outburst which is bright in gamma radiation and a common outburst which is bright in optical light.

Many proposed GRB models do not admit the possibility of recurrence (Baan 1982, Teller and Johnson 1980, Brecher 1982, Zwicky 1974, Grindlay and Fazio 1974). Of course, any of these mechanisms may account for some subset of observed GRBs.

The thermonuclear flash model (where the matter is accreted from the interstellar medium) has difficulty in attaining a sufficiently high accretion rate to account for the short recurrence time scale. For typical densities of the interstellar medium and for Woosley's (1982) estimate of the total mass required for ignition, the velocity of the GRB with respect to the accreting gas must be less than ~2 km/sec. However, if the GRB is a lone neutron star, then we might expect it to have a similar space velocity as the pulsar population (typically of ~300 km/sec; Manchester and Taylor 1977). Bonazzola et al. (1981) avoid this difficulty by suggesting that only the small fraction of neutron stars with low relative velocities will be GRBs. If the neutron star velocities are Maxwellian distributed with a mean velocity of 300 km/sec, then the fraction that will be GRBs is of order 10^{-7}. For this model, GRBs must be a disc population with a scale height of 100 pc (as that is the distribution of the interstellar medium). Since no large positional anisotropies on the sky are observed, the $\sim 10^2$ observed GRBs must be contained in a volume of less than $(4\pi/3)(100\text{pc})^3$. However, if $\sim 10^9$ neutron stars at

1.4 $M_{\odot}$ each are placed in this volume, Oort's limit on the invisible mass density (Spitzer 1978) is violated by over three orders of magnitude. It is possible to avoid this difficulty if GRBs are made from a population with low space velocities, as in the model of Ventura et al. (1983).

The asteroid collision model has difficulty in accounting for a recurrence time scale of roughly one year. Van Buren (1981) has calculated that if the source of asteroids is the interstellar medium, then the asteroid mass density violates Oort's limit on the invisible mass density by many orders of magnitude. If the asteroids are from a residual planetary system around a neutron star, then the predicted recurrence time scale is 10^6 times longer than observed. This is even after an enlarged capture radius (due to the drag of Alfven wave emission) and a Jupiter-like perturber are invoked. Another difficulty is that if the neutron star was formed by a supernova eruption, then the velocity kick on both neutron star and asteroid and the destruction of asteroids by the explosion will severely deplete the surviving asteroid population (Van Buren 1981, Colgate and Petschek 1981, and Hills 1983). A final difficulty arises whenever a companion around the neutron star is invoked as a means of perturbing some population of asteroids. Any perturber which can send asteroids towards the neutron star will also scatter (typically by ejection from the system) the parent population in a short time scale. For example, a Jupiter mass companion would deplete the population of perturbable asteroids on a time scale of 10^4 years (G. Wetherill 1983, private communication). After this short period of scattering, the perturber will no longer be effective at increasing the asteroid collision rate.

The thermonuclear flash model (where matter is accreted from a companion star) predicts that the recurrence time scale could be from months to centuries (Woosley 1982).

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Table I. Comparison of Transient Images

1928 Optical Transient	1901 Optical Transient	1944 Optical Transient
In GRB error region for 19 Nov 1978 GRB	In GRB error region for 5 Nov 1979 GRB	In GRB error region for 13 Jan 1979 GRB
Not on plate taken 45min earlier	Not on plate taken a month earlier	Not on plate taken 5 days earlier
Not on plate taken 45min later	Not on plate taken a month later	Not on 3 plates taken 2 days later
Apparent mag. - $10\overset{m}{.}2$	Apparent mag. - $13\overset{m}{.}7$	Apparent mag. - $12\overset{m}{.}1$
Faintest star - $16\overset{m}{.}0$	Faintest star - $14\overset{m}{.}2$	Faintest star - $14\overset{m}{.}0$
Magnitude(t=1s) - $3\overset{m}{.}0$	Magnitude(t=1s) - $6\overset{m}{.}6$	Magnitude(t=1s) - $4\overset{m}{.}3$
Normal stars trailed	Normal stars trailed	Normal stars trailed (?)
Transient untrailed	Transient untrailed	Transient untrailed
Transient shows coma	Image near plate center	Image near plate center
Profile is shallower	Profile is shallower (?)	Profile is shallower (?)

Figure I. The 1901 Optical Transient.

The top panel shows a portion of the plate B28642 (with a blowup in the lower panel) which contains the 1901 transient image. Note that the transient image (indicated by tic marks, in the lower panel) is circular while the other images are trailed by 8".

Figure II. The 1944 Optical Transient.

A small portion of the plate AM23468 which shows the 1944 transient image (indicated by tic marks).

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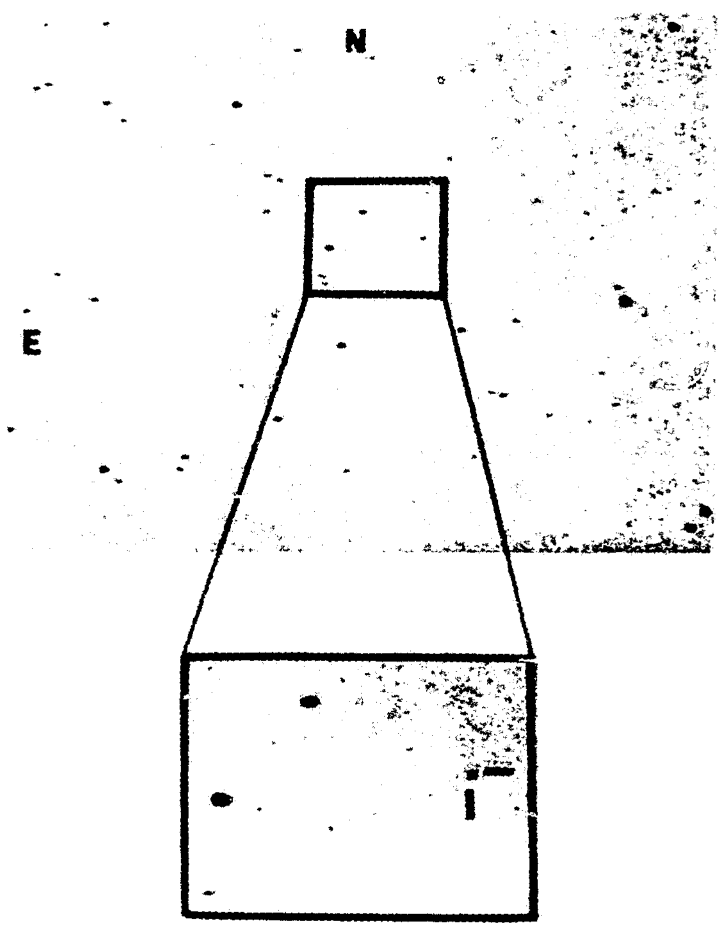

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