A SEARCH FOR OPTICAL FLARES AND FLASHES WITH A LIQUID-MIRROR TELESCOPE

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ABSTRACT

We have used two liquid-mirror telescopes of 1.2 and 1 m diameters to search for optical phenomena that occur in the sky with short timescales (less than 2 min). We obtained a total of 130 hr of usable data. We did not find any event. This search shows that optical flashes and flares are rare events. Our data are useful for setting limits to the frequency of such events. The most noteworthy part of this work comes from the fact that this is the first time that a liquid mirror has been employed in a scientific project.

I. INTRODUCTION

Very little is known about optical phenomena that occur in the sky with short timescales (less than a few tens of seconds). This has been emphasized by several writers (Bondi 1970; Harwit 1981; Schaefer et al. 1987a,b). Recently, some effort has been made to find optical flashes associated with gamma-ray bursters (Schaefer et al. 1987a,b, and references therein). There have, however, been very few searches for optical flashes in random regions of the sky. The most notable one is by Schaefer et al. (1984), who photographed regions of the sky simultaneously with two widely separated Schmidt telescopes. Schaefer (1985) conveniently summarizes and analyzes the situation up to that time. The subject has become important since the discovery reported by Katz et al. (1986) of a rapid optical flasher in Perseus. The Perseus flasher is now, however, believed to be of a nonastronomical origin (Halliday, Feldman, and Blackwell 1987; Malley 1987; Schaefer et al., 1987a,b). This lack of data about rapid phenomena is easy to understand because it is difficult to secure the large quantity of telescope time necessary for this kind of project. The tedious analysis of the large quantity of data generated is also a deterrent for what is a "long-shot" project.

We have lately been experimenting at Laval University with liquid-mirror telescopes (Borra 1987; Borra et al. 1985; Borra, Beauchemin, and Lalande 1985; Borra, Content, and Boily 1988). This provides us with inexpensive telescopes to which we have unlimited access. At the same time, we wanted to operate this kind of telescope in an astronomical context to check on its performance. We decided, therefore, to spend two summers to search for optical flashes and flares with liquid mirrors. The data obtained have also been used to evaluate the performance of the two liquid-mirror telescopes used (Borra, Content, Poirier, and Tremblay 1988, hereafter referred to as Paper I). In this paper, we discuss the results of our search for optical flares and flashes.

II. OBSERVATIONS AND DATA REDUCTION

a) Telescope and Detector

We observed in the summer and fall of 1986 with a 1 m liquid mirror and in the summer of 1987 with a 1.2 m liquid mirror. In each case, a 1 m telescope was used on 42 clear nights and gave us a total of 206 hr of data on film, but for a variety of reasons (Paper I), having to do with inadequacies of the setup and the inexperience of many of the observers, only 58 hr of the 1986 data were useful for the purpose of this paper and analyzed. The 1.2 m telescope was used in 1987 on 21 clear nights for a total of 74 hr of data on film. The setup was improved in 1987, and 62 hr of these observations were usable. The telescopes and observatory were very simple and are more fully described in Paper I. In Paper I we also discuss in detail the experimental procedure and the quality of the data. The telescope is a zenith instrument and observes the strip of sky passing at the zenith of the Laval University campus (latitude = 46°46′54″). The 1 m telescope was operated from 20 June 1986 to 25 October 1986. The strip of sky observed in 1986 is thus centered at a 1986 declination of 46°46′54″, starts at a 1986 right ascension of 13°43′, and stops at a right ascension of 3°12″. The field subtended by a 23.5 × 35 mm frame was 17.6 arcmin wide (on a scale of 44 arcsec mm⁻¹) for the 1 m telescope. The 1.2 m telescope was operated from 30 June 1987 to 21 August 1987. The strip of sky observed in 1987 is thus centered at a 1987 declination of 46°46′54″, starts at a right ascension of 18°26′, and stops at a right ascension of 1°28′. The field of the 1.2 m was 15 arcmin wide (scale of 38 arcsec mm⁻¹).

The detector was very simple, consisting of a programmable 35 mm camera. We used film having Kodak 2475 emulsion, which we developed in DK-5. This emulsion was chosen for its high speed (4000 ASA). We used a Lumicon Deep-Sky filter designed to minimize light pollution from urban sources. This has a 900 Å bandpass transmitting from 4420 to 5320 Å, plus a red transmission from 6400 to 9000 Å. We measured the transmission curve of the filter and this is shown in Fig. 1. Even during moonless nights, 2 min exposures show some background. The camera was programmed to take series of 2-min-long exposures. We did not have any tracking, and stars therefore give trails 2 min (20.6 arcmin) long. Paper I gives reproductions of several of our frames as well as quantitative analyses of some of the trails.

b) Magnitude Measurement

We must estimate the limiting magnitude of every frame for the statistical evaluation of our search. Ideally, we would like to have a calibrated photoelectric sequence for every field; this is obviously not practical. Furthermore, with such a large number of exposures, and a small number of images in each frame, it was not possible to measure the limiting magnitude directly in each. Instead, the magnitude limit was estimated in each frame using an expression based on measurements made with a Joyce Loebi microdensitometer. In this section, an expression for the magnitude of an image on
the film is derived. In the following two sections, this is
generalized to give the limiting magnitudes of star trails and
then flash events on a given film.

Our photographic frames are not calibrated with a spot
sensorium; we therefore use the characteristic curve for
2475 emulsion developed in DK-50 for our development
times (Eastman Kodak 1975). The true characteristic curve
is probably not identical to this, but the error introduced
should not be great, especially considering that the sky back-
ground and the density profiles are always in the linear part
of the characteristic curve. To relate density $D$ to exposure
$E$, the following relation was used based on the Kodak data:

$$D = \gamma \log \left[ (C + E/E_0 \gamma) \right],$$

where $C$ is a constant and the value of $E_0$ and the slope $\gamma$ are
given by the following expressions which allow for recipro-
city failure as a function of the effective exposure time $t_2$
in seconds:

$$E_0 = 0.6(10t_2)^{0.25},$$

$$\gamma = \gamma_0[1 + 0.1 \log (10t_2)].$$

We can now derive an expression for the magnitude of a
stellar image based on three measurements: the FWHM of
the image $w$ (measured at the density corresponding to half
the peak intensity), the sky-background density $D_0$, and the
peak density above sky $\Delta D$ of the image. In the case of a star
trail, the exposure time is the time taken for the image to
move a distance $w$, and is given by $t_2 = 20000 \ (w/f)$, where
$f$ is the focal length of the telescope. The value of $f$ and $\gamma_0$
were different for the two telescopes and are given in Table I.

From the above, it is straightforward to obtain an expression
for the intensity $\Delta I$ corresponding to a given image density
above the sky $\Delta D$ as

$$\Delta I = \gamma E_0 10^{\Delta D/\gamma} (10^{\Delta D/\gamma} - 1)/t_2.$$

We can then write the magnitude of the object in terms of
this peak intensity and the image diameter $D$ (in arcseconds) as

$$m = -2.5 \log (\Delta D^2) + M_0 + M_2,$$

where $D = 10.3r_2$, $M_0$ is a correction of 0.5 mag to be added if
the telescope was operated without Mylar protective film
(see Paper I), and $M_2$ is a constant to be determined by
calibration. Expanding this equation, we obtain

$$m = -2.5 \log \left[ 113.2\gamma t_2^{1.25}(10^{\Delta D/\gamma} - 1) \right]$$

$$-2.5D_0/\gamma + M_0 + M_2.$$  

The $f$ ratio was essentially the same for both mirrors, hence it
is a constant which was added to $M_2$. To calibrate the magni-
tudes, we would ideally have a photometric sequence for
every field; this is obviously not practical. We instead cali-
brated our frames indirectly using photometric sequences
obtained as part of a Space Telescope Science Institute
(Lasker et al. 1988) calibration effort. We used Palomar
Observatory Sky Survey (POSS) prints of fields containing
the photometric sequences as well as the strip of sky that we
observed. Following the procedure of King and Raff (1977),
we calibrated the relation between image diameters on the
survey prints and $B$ and $R$ magnitudes. The image diameters
on the POSS prints were estimated with a binocular micro-
scope and a graduated scale. The results were compatible
with those previously obtained by King and Raff (1977)
within the uncertainties ($\pm 1$ mag). Therefore, we used the
King and Raff (1977) relations to obtain $B$ and $R$ magni-
tudes of stars in our fields.

The calibration of our films is complicated by the unusual
response of the deep-sky filter used. The passbands mean
that the film actually records a sum of blue and red intensi-
ties, although an approximate calculation using the conven-
tion of magnitudes normalized by the spectrum of Vega and
the spectra response of the film given by Kodak showed that
the blue component contains approximately three times as
much energy as the red component. We defined a natural
magnitude scale for our system allowing for the two con-
tributions. The final magnitude is close to $V$ and may be written
as

$$m_L = V - 2.5 \log_{10}$$

$$\times \left[ \left( 10^{-0.24(B - V)} + 0.4(10^{0.17(B - V)}) \right)/1.4 \right].$$

Note that in order to calibrate our stars from the POSS
prints we had to make a further correction to convert $R$
values to $V$ using the expression given by King and Raff
(1977). All magnitudes given below are in this system.

The magnitude expression was calibrated by measuring
stars of known magnitudes with a microdensitometer. Sever-
al different stars on the same film were measured first in
order to reduce statistical errors arising from uncertainties
in the POSS magnitudes. Two stars were then measured on
a number of different films taken under varying conditions
to obtain a measure of the dispersion due to our measurement
errors. The value of the calibration magnitude obtained was
$M_2 = 12.5 \pm 0.5$. The uncertainty was greater for the 1986
data, and there is evidence for a small drift in the magnitude
limit with time for the data at the end of the 1986 session
which has also been modeled in the calculations.

| Table I. Values of various parameters of the telescopes used in the two observing seasons. |
|----------------------------------|--------------|--------------|
| 1986 | 1987 |
| Diameter | 1.0 m | 1.2 m |
| Scale | 43.9 arcsec/mm | 37.5 arcsec/mm |
| Focal length | 4.7 m | 5.5 m |
| $\gamma_0$ | 0.94 | 1.54 |

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c) Limiting Magnitude

To determine the detection limits for flares, we need the limiting magnitude on each of the exposed frames. This section describes the calculation of the limiting magnitude for a normal star trail, and in the following section this is generalized to describe a flash.

Although the search was made by eye, considerable care was taken to quantify the detection criteria. The major criterion is the minimum photographic density above sky detectable by eye. This was measured by taking the faintest traces visible on several different films. The following relation was obtained for the minimum density difference detected:

$$\Delta D_{\text{min}} = 0.12 \times 10^{-3} (D_0 + 0.7) / \sqrt{w},$$

where $D_0$ is the sky-background density and $w$ is the width on the film (FWHM) measured in meters. This expression corresponds to a $\Delta D_{\text{min}}$ proportional to the background noise. The rms dispersion on the constant $1.2 \times 10^{-3}$ was 20%. The $(D_0 + 0.7)$ factor was obtained from the noise measured on our frames and is consistent with the noise given in Eccles, Sim, and Tritton (1983). The limiting magnitude for a star trail is simply given by substituting this minimum-difference density in the magnitude derived above in Eq. (6):

$$m_{\text{min}} = -2.5 \log \left[ 3.13 \times 10^{-2} \frac{1.25 (D_0 + 0.7)}{\sqrt{w}} \right] - 2.5 D_0 / \gamma + M_\gamma + M_L.$$  

This expression was then used to estimate the limiting magnitude of each frame. Because of the large number of films, we did not make any correction for frame-to-frame variations of the sky background, instead taking an average value for each film. With the exception of some very dark frames, the sky background does not vary much from frame to frame. Unusually dark frames were discarded. The seeing was not the same on all nights and, because of our crude focusing technique, the focus was probably seldom optimized (Paper I). This was more of a problem in 1986 when most of the observers were inexperienced and sometimes made large focusing errors. The 1987 observations were taken mostly by a single (and by then) experienced observer (SP). The 1986 observations had an additional bothersome problem: the liquid mirror was driven by a poor-quality power supply. This resulted in slow focus drifts: the focus was often better at the beginning of a roll than it was at the end. The widths of the trails thus get progressively larger from the beginning of a film to the end, the limiting magnitude thus decreasing with time within a film. To take these drifts into account, we measured the FWHM of trails on frames at the beginning, middle, and end of every roll of film.

The widths of the trails of every frame are estimated from linear interpolations (as a function of frame number) among these three measurements. In 1987 we used a new, better-stabilized power supply, the telescope did not experience noticeable focus drifts, and the three measures of the FWHM agree reasonably well.

Applying the expression to the films gave typical limits of $m = 11$, compatible with independent estimates based on starcounts in the fields. Comparison with visual estimates of the faintest magnitude in selected frames confirmed the theoretical limits computed for those frames.

d) Limiting Flash Magnitude

The detection of a flash or flare depends on the length of the event; for long flares the image resembles an ordinary star trail and we can use the above results for the magnitude limit. However, for shorter events, the sensitivity is reduced in a way that is not necessarily proportional to the length of the flash. The limiting magnitude for the detectability of a flash is obviously a function of its duration. Because the eye tends to group together the nearby grains of a faint star trail, it should be expected that, for the same peak magnitude, long-lasting flashes are easier to see than rapid ones. To simulate flashes of varying duration, we took a film exposed, but not developed, and introduced artificial flashes by opening the shutter at 60, 30, 15, 8, 4, 2, 1, 1/4, and 1/8 exposure times. To quantify this relationship, we can rewrite the minimum density of a flash detectable as a function of the length of the flash:

$$\Delta D_{\text{min}} / (D_0 + 0.7) = g(L) / \sqrt{w},$$

noting that $L$, the length of the flash trail in meters, is given by

$$L = \int \left[ w^2 + (t_i / f / 20000)^2 \right]^{1/2},$$

where $t_i$ is the duration of the flash in seconds and $g(L)$ describes the variation of the sensitivity with the length of the flash trail. Note that $g$ should also be a function of $w$ but the dependence is not significant here. For a long flash ($L \gg w$), we simply have the equivalent of a star trail and $g(L) = 0.12 \times 10^{-3}$. For very short flashes, the image is basically a point and so we instead obtain $g(L) \sqrt{w} = 2.5 \times 10^{-5}$. For intermediate flash times, the relation was calibrated using the test exposures above to give the curve shown in Fig. 2. For this calibration, we use $1 / \sqrt{L}$ instead of $L$ as the variable to obtain a straight line when $L$ is small. The constant $2.5 \times 10^{-5}$ is obtained from this line. It should be noted that this relation has not been measured directly in

![Fig. 2. Variation of sensitivity $g(L)$ with respect to $L^{-1/2}$, where $L$ is the length of a flash in meters. The dashed line shows the linear relation used for small $L$.](image-url)
previous work. For instance, the analysis of Schaefer et al. (1984) assumes a constant value of $g(L)$, as if the minimum detectable density was the same for a star or asteroid trail and a flash point. Consequently, they may overestimate their sensitivity to flashes by up to 2.5 mag. To investigate this, we looked for minimum detectable density on a HIa-J grens plate obtained with the Canada–France–Hawaii Telescope. The grens gives slittless spectra and records multiple orders. The zero order is essentially stellar, while the multiple orders are elongated and look like star trails. This provides us with simulated data to verify the detectability of trailed and untrailed images. We find that a spectrum 2 mm long and 0.1 mm wide is detectable at a density above background 4 times smaller than a zero order having 0.2 mm length and 0.1 mm width. So, for a ratio of length 10 we have a difference of 1.5 mag, with the assumption that the minimum detectable density is independent of $L$. Considering that the ratio of star-trail length to flash-point length is also 10 in the work of Schaefer et al. (1984), we conclude that their sensitivity is overestimated by approximately 1.5 mag.

We can include this expression for the minimum density in Eq. (9) to obtain a limiting flash magnitude as a function of time. The magnitude has the same form as before:

$$m_{\text{lim}} = -2.5 \log(A) - 2.5D_0/\gamma + M_{r} + M_{z},$$

(12)

except that the part $A$ has one of two forms, depending on the length of the flash. For a short flash of duration $t_1 < 0.1$ s, we use the asymptotic limit that $g(L)\sqrt{w} = 2.5 \times 10^{-2}$ and the fact that there is no reciprocity effect; hence,

$$A = 1.47 \times 10^{0.29} (w/f^2) (D_0 + 0.7)/t_1,$$

(13)

while for longer flashes we must first define an effective exposure

$$t = t_1 (1 + (t_1/t_2)^2)^{1/2},$$

(14)

and we obtain

$$A = 1.05 \times 10^{0.29} (w/f^2) (D_0 + 0.7) g(L)/t^{0.75},$$

(15)

These expressions were used to estimate the limiting flash magnitude on each film as a function of flash duration, and the results are summarized in Sec. III below.

e) Search for Flare Events

The 35 mm rolls are inspected by eye and any abnormal phenomenon is recorded. In particular, we look for optical flashes that should give trails shorter than the 2-min-long trails expected from an object having a constant luminosity. We also look for the brightening of star trails that should reveal flares in stars. Photographic emulsions are prone to defects (e.g., static electricity discharges). Also, real light events in the sky may be due to nonastronomical phenomena (satellites, airplanes, etc.). The presence of a short trail or flare is therefore not necessarily indicative of an astronomical event. We have only a single telescope, hence we have neither an independent check nor parallactic information. We must rely on the appearance of the event (width, length, orientation, and structure) as a clue to its origin. All candidate events are scrutinized in detail with a binocular microscope under a variety of magnifications. The low depth of field of the high magnification (70X) was particularly useful to eliminate traces of dirt as candidates.

We found a couple of dozen "events" in our frames, but none of these looks like a convincing case for a flash. Typically, the image of an "event" looks rounded, with a very small dark core surrounded by a diffuse halo. The core is typically smaller than the seeing by a factor of 2, which shows that they cannot originate outside the atmosphere. These "events" are obviously emulsion defects. Some of these events were found outside the exposed frame, clearly indicating that they are emulsion flaws. We found a single meteor trail. We did not detect any flare in stars.

III. DISCUSSION

Our data are in agreement with the results of previous work: flashes and flares in the sky are very rare events. Schaefer (1985) has estimated the flash rates $R$ per steradian per hour, expected from various sources of flashes and flares. For comparison to his computations, our data can best be presented in terms of $R$ as a function of limiting magnitude $m$.

$$R(m) = 1/(\omega t(m)),$$

(16)

where $\omega$ is the solid angle subtended by a 35 mm frame ($\omega = 3.94 \times 10^{-5}$ sr for the 1 m and $\omega = 2.86 \times 10^{-7}$ sr for the 1.2 m) and $t(m)$ the total observing time for the limiting magnitude $m$. Figure 3 shows $t(m)$ for trails at least 60 s long and Fig. 4 shows log $R(m)$ for 0.1, 1, 10, and 60 s flash durations. When comparing our Fig. 4 to Schaefer's Fig. 2, we see that our values of log $R$ are comparable to those obtained by the other surveys. Note, however, that Schaefer uses 99% confidence levels; hence one should add 0.66 to our values in Fig. 4 for such a comparison. Comparison to the rates predicted for various flash sources in his Fig. 1 indicates that our search is not sensitive enough, by several orders of magnitude, to detect gamma-ray bursters.

Our main motivation for this experiment was to operate an LMT in an astronomical environment (at the same time as optical tests are carried out in our shop) and demonstrate its scientific use. We did not have much money nor resources to dedicate to this project; as a consequence, the experiment was not optimized to search for flashes. The liquid-mirror telescope itself was a prototype and quite rudimentary. Technical improvements would now allow us to build much better instruments. For example, we have recently worked with thin mercury layers that allow us to work without Mylar. We have obtained with a 1.5 m thin-layer liquid mirror images having FWHM = 0.25 arcsec in our testing facilities.

Liquid-mirror telescopes are ideal instruments for survey work for they are inexpensive and can thus be dedicated full time to a specific project such as a search for rapid phenomena. It is therefore of interest to examine the design and performance of an LMT optimized for this type of work. Equation (16) clearly shows the importance of having a telescope that has a wide field of view. The telescope should be designed around existing CCD chips and have the widest possible field of view. For the sake of discussion, we assume a $512 \times 512$ CCD having 25 $\mu$m pixels. A resolution of 5 arcsec/pixel seems a good compromise between a wide field and a good angular resolution. This leads to a telescope having a focal length of 1 m. A single CCD then measures 43 arcmin across and covers 0.5 sq. deg. The telescope would have to integrate for 6500 hr to obtain log $R = 0$. This corresponds to 800 clear nights and therefore about 4 yr of observing in a good site.

The most competitive design to which we can compare this design is the Explosive Transient Camera (ETC) of Ricker et al. (1984). The ETC achieves log $R = -3$ in 1 yr through a very wide field (3 sr) and several CCDs, but at the cost of low resolution (6 arcmin/pixel) and a relatively
bright limiting magnitude \( (V<11) \). We can obviously achieve fainter limiting magnitudes with a larger LMT and increase the field with several CCDs and perhaps several LMTs. If we consider again a 1 m diam \( f/1 \) LMT and put four CCDs in the focal plane, we can achieve \( \log R = 0 \) in 1 yr. Using four CCDs necessitates a field of view of over 1.5°. Correctors achieving 5 arcsec resolution over 1.5° should be feasible. For example, the Paul–Baker corrector has been shown to achieve 0.2 arcsec over a 1° field with \( f/1 \) parabola.

The performance of the optimized 1 m LMT is still three orders of magnitude inferior to the ETC if we consider only the log \( R \) criterion. However, an LMT would have better resolution, allowing one to obtain the exact position and identification of the burster, and fainter limiting magnitudes. It would also allow one to better study flare stars and other phenomena. The best way to detect transient phenomena with a CCD is to generate star trails and detect flares and flashes with software in a similar way as we did visually with the present experiment. The simplest way to trail is not to track; the Earth rotation will then cover 1 pixel in 0.385 s at a terrestrial latitude of 30° thus giving this time resolution. Let us assume that we read out the CCD every 10 s. The quantity of data generated is huge but probably manageable with
dedicated microcomputers that reduce the data in real time. We
compute the limiting magnitude in the V band for S/N = 5, a flash that lasts 1 s, and a sky exposure of 10 s: it is
V = 17.6, almost 7 mag fainter than the ETC. Schaefer
(1985) predicts a log R = 0 for gamma-ray bursters at
V = 18. The LMT should thus detect about 1 event/yr while
Schaefer (1985) predicts about 20 events/yr for the ETC.
We can conclude that, in practice, because of uncertainties in
the prediction of log R(m) for gamma-ray bursters, the
ETC and a single 1 m dedicated LMT should have about
equal performance, the LMT having the advantage of much
higher spatial resolution.

To detect flares in stars, our LMT has a considerable ad-
vantage over the ETC, for the rate of flares detected is pro-
portional to the diameter of the objective, for a given de-
tector and f ratio. Schaefer (1985) predicts R = 3.9 for
V = 17.6; this gives 3000 flares/yr with one LMT, one CCD,
and a time resolution of 0.385 s. If we integrate over 10 s, we
obtain 400 000 flares/yr with that time resolution and S/
N = 5.

IV. CONCLUSION

We searched for rapid optical phenomena in the sky dur-
ing this summer and fall of 1986 and during 2 months in the
summer of 1987. We did not find any flash: the sky is there-
fore not full of bright objects that flash with short recurrence
timescales. If such objects exist, they are rare. Our data are
useful for setting limits to the frequency of such events.
The most noteworthy part of this work probably comes
from the fact that this is the first time that a liquid mirror has
been employed in a scientific project.

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