RESULTS FROM THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT (OGLE)

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Abstract. The analysis of the first three years of the OGLE data revealed 12 microlensing events of the Galactic bulge stars, with the characteristic time scales in the range $8.6 < t_0 < 80$ days, where $t_0 = R_E/V$. A complete sample of nine events gave the optical depth to gravitational microlensing larger than $(3.3 \pm 1.2) \times 10^{-6}$, in excess of current theoretical estimates, indicating a much higher efficiency for microlensing by either bulge or disk lenses. The lenses are likely to be ordinary stars in the Galactic bar , which has its long axis elongated towards us. At this time we have no evidence that the OGLE events are related to dark matter . The OGLE color magnitude diagrams reveal the presence of the Galactic bar and a low density inner disk region $\sim$ 4 kpc in radius. A catalogue of a few thousand variable stars is in preparation.

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1. Introduction

The OGLE project (Optical Gravitational Lensing Experiment) is a collaboration between the Warsaw University Observatory, Carnegie Observatory, and Princeton University Observatory. All observations are done with the 1 meter Swope telescope at the Las Campanas Observatory, operated by the Carnegie Institution of Washington. We have the telescope available to the OGLE about 70 nights each season, which lasts from early April to early September, when the Galactic bulge can be observed. The detector is a single Loral CCD with $(2k)^2$ pixels. A somewhat modified DoPhot photometric software (Schechter, Mateo & Saha 1993) is used to extract stellar magnitudes from the CCD frames. All data is processed at the observing site with a Sparc 10/512 computer within 24 hours of the acquisition, and the summary of the results is e-mailed to the Warsaw University Observatory for evaluation, off-loading the observer who is on duty. All technical details and the journals of the observations are provided in Udalski et al. (1992, 1994a). The project covered three observing seasons: 1992, 1993, and 1994, and it is likely to continue in the same form through 1995.

Some time in 1995 a new 1.3 meter R/C telescope will be put into operation at the Las Campanas site. It will be managed by the Warsaw University Observatory, and it will be dedicated to massive CCD photometry, the search for gravitational microlensing being one of the prime projects. Two other large collaborations are involved in a search for gravitational microlensing of the LMC stars as well as the Galactic bulge stars (Alcock et al. 1993; Aubourg et al. 1993; see also these Proceedings).

2. Results

Whenever the Galactic bulge was observable and the seeing was adequate we were monitoring 13 fields in the bulge region in 1992, and 20 fields in 1993 and 1994, each field being $\sim 15' \times 15'$ in size. The distribution of the fields in the sky is shown in Stanek et al. (1994b, cf. Fig. 1., these Proceedings) The total of 12 lensing events was discovered: 7 in 1992, 3 in 1993 and 2 in 1994 (Udalski et al. 1993a, 1994b,c,d,e). The location of 11 of those lenses in the color magnitude diagram (CMD) is shown in Fig. 1. It is clear that the lenses are scattered over the part of the diagram where the Galactic bulge stars are found.

A careful statistical study of a complete sample of nine events found in the data from 13 fields observed in 1992 and 1993 confirmed the impression that the distribution of those nine events was random in the CMD, and their amplitude distribution was random as well, allowing for known biases in the detection procedure (Udalski et al. 1994e). In the same paper the optical depth to microlensing was found to be larger than $(3.3 \pm 1.2) \times$

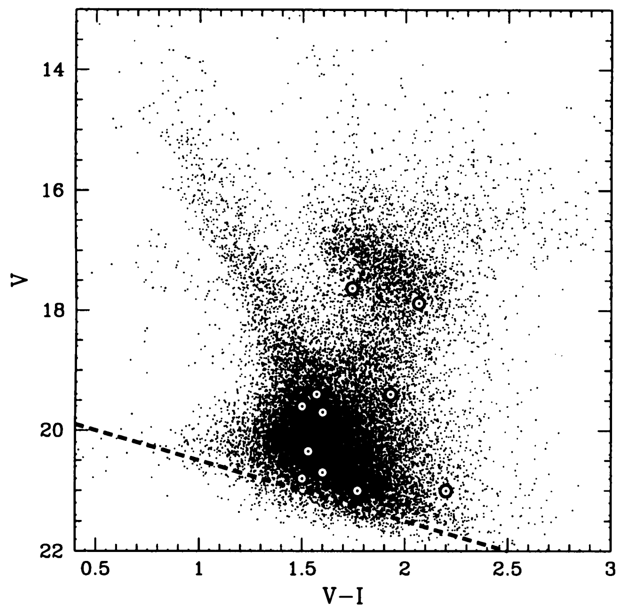

Figure 1. The locations of the 11 OGLE lensing events (large circles) are shown in the color – magnitude diagram for Baade's Window and the Galactic bar fields combined. Only $\sim 5\%$ of all stars are shown. The dashed line shows the limit of lenses detectability given by the condition $I < 19.5$. A calibrated photometry of one of the 12 OGLE events is not available at this time.

10^{-6}, in excess of original theoretical estimates, indicating a much higher efficiency for microlensing by either bulge or disk lenses. We argued that the lenses are likely to be ordinary stars in the Galactic bar, which has its long axis somewhat inclined to the line of sight (Paczyński et al. 1994b). Two examples of the microlensing events are presented in Fig. 2.

Another major highlight was the development and implementation in the 1994 season of the "early warning system", EWS (Paczyński 1994a, Udalski et al. 1994c). The data from every clear night were automatically analyzed by the on-site computer system (Sparcstation 10/512), and the summary of results was automatically forwarded by e-mail to Warsaw. Two lensing events, OGLE #11 and OGLE #12 (Fig. 3), were detected on their rise on July 8 and August 20, 1994, respectively, making it possible to follow them up in detail.

The first fairly spectacular case of a microlensing by a double star, OGLE #7, was found in the 1993 data (Udalski et al. 1994d). The observed light curve, shown in Fig. 4, exhibits a sharp peak due to the source star crossing an optical caustic in the lensing system. Theoretical modeling predicted that a second sharp peak should be present in the gap of the

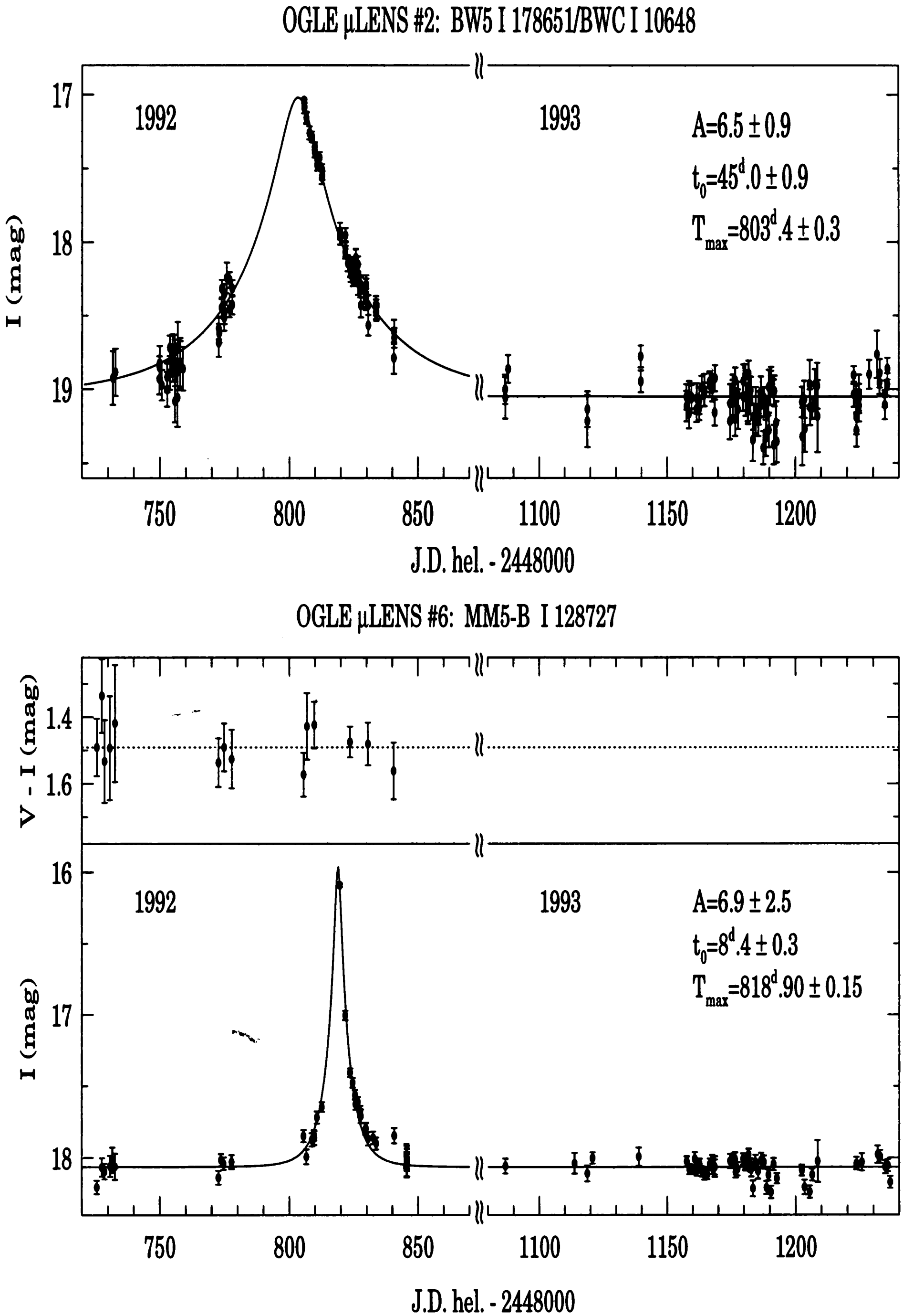

Figure 2. Examples of two microlensing events: long-lasting (upper panel) and short-lasting (lower panel) (Udalski et al. 1994b,e).

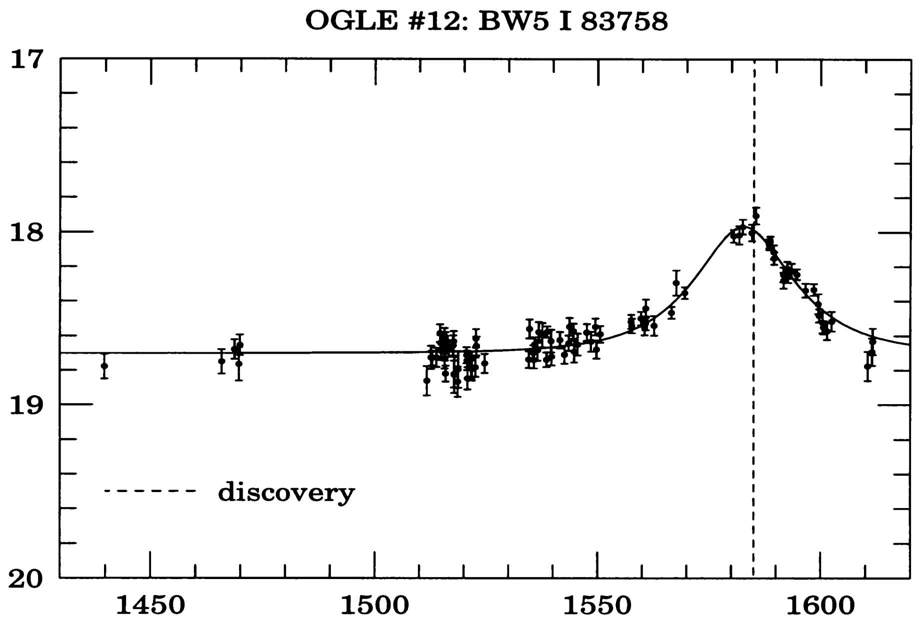

Figure 3. The second microlensing event detected by the OGLE Early Warning System and observed in real time (Udalski et al. 1994c). The dashed vertical line marks the date the event crossed the detection threshold – August 20, 1994. The first event ever to be detected in real time, OGLE #11, crossed the detection threshold on July 8, 1994.

OGLE data. Following the OGLE discovery of the event #7 the MACHO collaboration found the object in their data, and the presence of the second sharp peak of the light curve has been confirmed (Ch. Alcock, private communication). Thanks to the "early warning system" it will be possible in the future to obtain very good time coverage of such peaks in the light curves of double lensing events, which in turn will allow detailed studies of normally very faint stars. Events like that resolve the disks of the lensed stars just like stellar eclipses do. Brightening by more than five magnitudes is possible in some cases.

The color magnitude diagrams of the bulge region (Udalski et al. 1993b) turned out to be very useful source of information about the galactic structure. Stanek et al. (1994a,b) found that the red clump stars (the cloud of points around $V - I = 1.9, V = 17$ in Fig. 1) in the Galactic bulge were 0.37 ± 0.025 mag brighter at (l,b) = $(+5.5^o, -3.5^o)$ than at $(-5.0^o, -3.5^o)$, indicating the bulge is shaped as a bar, with the end at positive galactic longitude being closer to us.

The distribution of the galactic disk stars turned out to be unexpected. The disk main sequence stars form a surprisingly narrow band, traceable from $(V-I, V) = (0.9, 15)$ to $(1.4, 19)$ in Fig. 1. The analysis of the observed

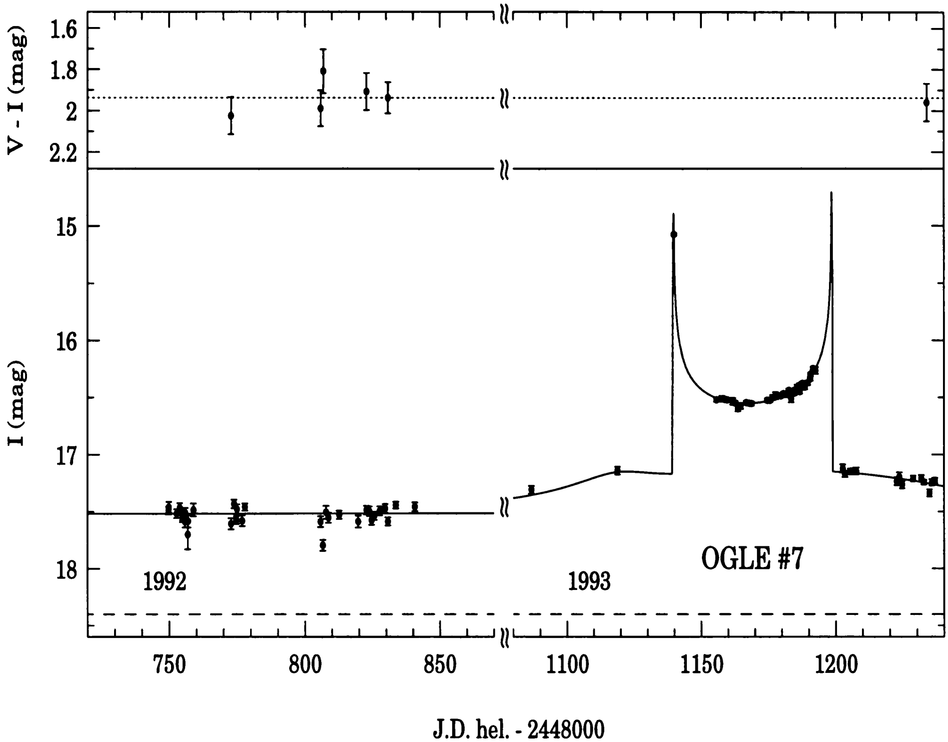

Figure 4. OGLE #7 – the first clear case of lensing by a binary system (Udalski et al. 1994d).

distribution pointed to a rapid drop in the number density of disk stars at a distance $\sim$ 3 kpc from the Sun (Paczyński et al. 1994a). These are the disk stars which may contribute to the lensing of the bulge stars, and the structure is apparent down to at least $M_V \approx 7$, i.e. it includes the old disk population. The evidence that the inner disk may have very few moderate age stars was available for some time (Baud et al. 1981, Blommaert et al. 1994).

In a systematic search for periodic variable stars thousands were found, and the catalogues are in preparation using the database of the OGLE photometry (Szymański & Udalski 1993). These are mostly contact binaries, other eclipsing binaries, RR Lyrae and SX Phenicis stars.

When the Galactic bulge could not be observed we had a number of secondary targets. In 1992 a few dozen clusters of galaxies were monitored for about four months in an attempt to detect supernovae – none were found.

In 1993 one field in the Sculptor dwarf galaxy was monitored and over

200 RR Lyrae stars were detected (Kałużny et al. 1994). Some examples are shown in Fig. 5. A correlation was detected between the period and average V magnitude of RRab type variables. Also, two globular clusters, 47 Tuc and Omega Cen, were monitored in a search for detached eclipsing binaries. At least one such system was found in Omega Cen, approximately one magnitude above the main sequence turn-off point (Kałużny et al., in preparation).

In 1994 Omega Cen and 47 Tuc were monitored, and in addition some frames of one field in the recently discovered Sagittarius dwarf (Ibata, Gilmore and Irwin 1994) were taken. We detected seven RR Lyrae variables belonging to the dwarf, and these were used to determine the distance: 25.2 ± 2.8 kpc (Mateo et al. 1994). The color magnitude diagram was used to estimate the age to be ~ 10 Gyr.

Preliminary results from the OGLE were presented at a number of conferences (Szymański et al. 1993, Udalski et al. 1992b, 1993c)

3. OGLE Related Papers

There was a number of papers written as a consequence of the OGLE observations. Kiraga & Paczyński (1994) noticed that the major contribution to the optical depth to gravitational microlensing of the Galactic bulge stars is from the Galactic bulge stars themselves. Kiraga (1994) presented theoretical maps of the optical depth as a function of galactic coordinates. The high optical depth found by the OGLE was reproduced theoretically by Zhao, Spergel and Rich (1994) with their dynamical model of the Galactic bar, strengthening the case for the presence of the bar and for the bar origin of the majority of OGLE lensing events. Stanek (1994) noticed that the 'red clump' stars that are lensed should be systematically fainter than the general population of the red clump stars , and the shift in the median magnitude is directly proportional to the radial depth of the bulge/bar.

In general there is no unique relationship between the observed time scale of a microlensing event t_0 and the lens mass (e.g. Kiraga and Paczyński 1994). However, there is a case where the relation between t_0 and the lens mass is simple and unique. This is lensing of the Galactic bulge stars and LMC stars by globular clusters which are in front of them (Paczyński 1994b). This may be the most robust (though rather time consuming) way to determine the mass function of stars and brown dwarfs of which the globular clusters are made.

Renzini (1994) noticed that the very high number of the red clump stars observed by the OGLE in the Galactic bulge can be explained with the enhanced helium abundance of those stars, the enhancement related to their high heavy element content.

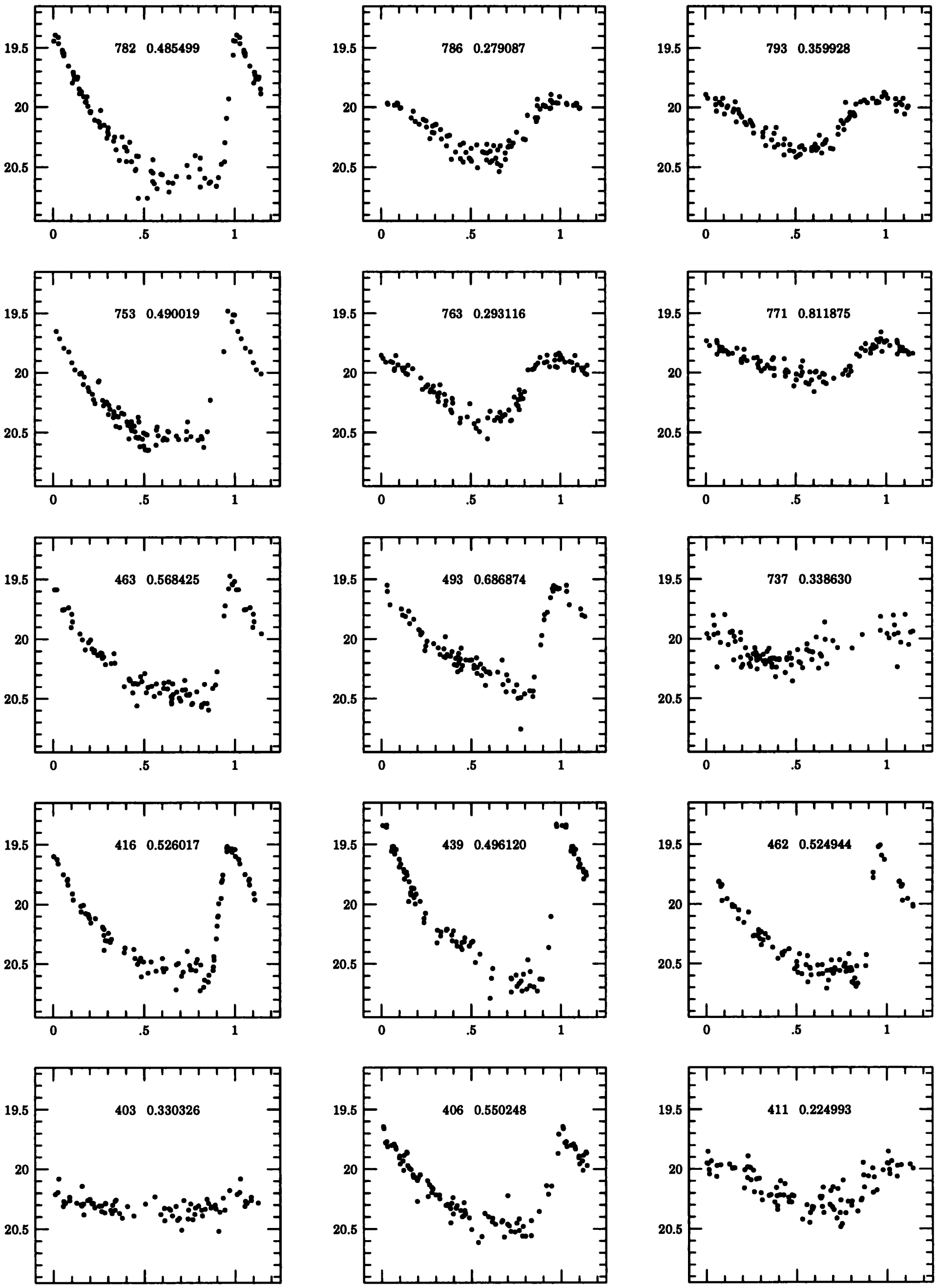

Figure 5. Examples of variable stars found in Sculptor dwarf galaxy (Kałużny et al. 1994) in V *mag*-phase diagrams.

Mao and Di Stefano (1995) developed a code to fit theoretical double lens light curves to the data, and noticed that the OGLE #6 event might be due to a double lens. The code was used to fit the observations of the OGLE #7 (Udalski et al. 1994d).

Many theoretical interpretation papers about the OGLE and MACHO events were written, but they are beyond the scope of this mini-review.

4. OGLE by Internet

Since the beginning of the 1994 observing season the OGLE project is capable of near real time data processing (Paczyński 1994, Udalski et al. 1994c). The new computer system automatically signals the events while they are on the rise, making it possible to carry out photometric and/or spectroscopic follow-up observations. The observers who would like to be notified about the on-going events should send their request to A. Udalski (udalski@sirius.astrouw.edu.pl). Two microlensing events have already been discovered with this system (Udalski et al. 1994c).

The photometry of the OGLE microlensing events, their finding charts, as well as a regularly updated OGLE status report, including more information about the "early warning system", can be found over Internet from "sirius.astrouw.edu.pl" host (148.81.8.1), using the "anonymous ftp" service (directory "ogle", files "README", "ogle.status", "early.warning"). The file "ogle.status" contains the latest news and references to all OGLE related papers, and the PostScript files of some publications, including Udalski et al. (1994c,e). The OGLE results are also available over "World Wide Web": "http://www.astrouw.edu.pl/".

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DISCUSSION

L. Blitz: Have you checked to see whether you have any triggering by events at the threshold level below the mean as a check to see that you are not getting similar events that would be spurious?

Paczynski: *answer not recorded.*