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The Microlensing Follow Up Network ($\mu$FUN) is an international collaboration of professional and amateur astronomers, dedicated to finding extrasolar planets by intensive monitoring of high-magnification microlensing events. Our experience leads us to conclude that extreme microlensing events (EMEs, with magnification $A > 500$) are the most productive for planet hunting: four out of the five we have intensively covered have yielded planets.

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## 1. Introduction

Since its founding in 2001, the Microlensing Follow Up Network ($\mu$FUN) has radically evolved in terms of its organization, composition, and approach to finding planets. We began by following the model laid out by Gould & Loeb (1992) and pioneered by PLANET (Albrow et al. 1998). That is, we attempted to form a network of telescopes dedicated to following up microlensing events discovered by OGLE and MOA, with the aim of detecting planets.

At first, we had only one dedicated telescope, the CTIO 1m in Chile, which was equipped with a two-channel optical/IR camera. We also had more limited access to the Wise 1m in Israel. This was "limited" in two senses. First, obviously, since Wise is well up into the northern hemisphere, it can only observe the Galactic bulge for limited periods each night. Second, Wise has many other ongoing programs, and so only partakes in microlensing observations when such observations are recognized as high priority. Actually, although we did not realize it at the time, both the optical/IR camera and the Wise "limited" commitment would end up playing a crucial role in our development.

But at the beginning, we were mainly focused on obtaining dedicated coverage from more telescopes at more longitudes. We used some of our grant money to rent the Mount Stromlo 74$''$ for 25 days per month, 4 months per year, with service observers doing the observing. The data quality was not very good, partly because of the optics, partly because of the seeing, and partly because the service observers were not invested enough in the project to track down whatever data quality issues could be fixed. This telescope was therefore quite expensive and the scientific payoff was low. The decision on whether to continue these observations was removed from our hands by the Mount Stromlo fire, which destroyed the 74$''$ and all other telescopes at the site.

We also sent then OSU grad student Jen Marshall to run the University of Hawaii 0.6m for a month to determine whether this could provide a viable link in our nascent network. We concluded it could not, partly because of data quality issues, but mainly because we doubted that rotating observers, who would generically have much less instrumentation skill than Jen, could keep it going.

These early years of $\mu$FUN were also hampered by a paucity of alerts coming from the search teams. OGLE has shut down their driftscan OGLE-II camera at the end of 2000, while they set up their much larger point-and-stare OGLE-III camera, which only started issuing alerts in May 2002. MOA had begun producing alerts, making up for some of the slack caused by the shutdowns of MACHO and EROS, but MOA-I was far less productive than MOA-II, which really started coming up to full speed only toward the end of 2007.

## 2. Jennie McCormick and the Transformation of $\mu$FUN

In 2003, I received an email from Jennie McCormick, saying "I have data on your target, what do you want me to do with it?" I had little expectation that an amateur operating a 12$''$ telescope in New Zealand, one of the wettest places in the world, could contribute significantly to our planet-detection capabilities, but in the interest of inclusiveness, I started sending her my $\mu$FUN circulars that identified key targets.

Nevertheless, Jennie's initiative had far-reaching effects on our group. For one thing, as a working mother, there was no way that she could observe every night. I therefore had to focus my requests on only the most important events and those most accessible to her small telescope. Thus, while continuing to apply our dedicated telescope in Chile to a wide variety of events, I began to pay increasing attention to high-mag events, which both have the greatest sensitivity to planets and are generally the brightest. Gradually, I began to realize that, in fact, these were just exactly the events we should focus all of our efforts on, and that our monitoring of "normal events" from CTIO was mostly a waste of observing time. Of course, Wise Observatory was already restricting observations to the most important events, but what was "most important" was now evolving to mean "high-magnification".

But Jennie's participation impacted our development from another angle as well. She contacted another NZ amateur, Grant Christie, who also joined out network. It should be said that Grant is an "amateur" only in the sense that he is not paid. He is a PhD engineer and has experience building and using telescopes for 40 years. Grant brought a level of expertise about amateur-class telescopes that was simply off scale. Moreover, his years of experience gave him contact with an international community of highly skilled amateurs, to which I will return shortly.

## 3. OGLE-2004-BLG-343

Another key development in our transformation was OSU grad student Subo Dong's analysis of OGLE-2004-BLG-343 (Dong et al. 2006). Of course, Griest & Safizedah (1998) had long ago pointed out the high sensitivity of high-mag events, and Rattenbury et al. (2002) subsequently elaborated this argument in the context of modern microlensing studies. Moreover, Abe et al. (2004) had analyzed a magnification $A > 500$ event, showing that it had some sensitivity to mass ratio $q = 10^{-5}$ (3.3 times that of Earth). However, Subo's study demonstrated for the first time that an event that was actually internally alerted as high-magnification (and so could have been observed) had good sensitivity to Earth mass-ratio planets. I should note that NASA has already spend more than \$1B developing satellites that *might one day* detect Earth-mass planets, the holy-grail of our subject. Hence, Subo's result that Earth-mass planets were *already* detectable with small ground-based telescopes radically refocused our thinking toward concentrating on the high-mag events.

The case of OGLE-2004-BLG-343 is instructive on several grounds. First, the internal OGLE alert came from the OGLE Early Early Warning System (EEWS). The OGLE EWS (Udalski 1994) has long been in place to provide alerts to community but, recognizing that their own routine modeling of ongoing events was often the best indicator of whether an event was becoming anomalous, OGLE developed a system of more-or-less instantaneous recognition of deviations of already-alerted events from standard microlensing. In order to avoid flooding the community with false alarms (due to cosmic rays, etc), the system first alerts the OGLE observer who then checks on the validity of the anomaly by making an additional observation. This system has provided crucial warnings of anomalies, including most dramatically, OGLE-2006-BLG-109 (see below).

Second, the extremely high magnification of the event was most likely due to the lens being a foreground disk star. Magnification peaks cannot be infinite: they are "cut off" by finite source effects, $A_{\rm max} \sim 2/\rho$, where $\rho = \theta_*/\theta_{\rm E}$ is the ratio of the angular source radius to the Einstein radius. Typical main-sequence stars have $\theta_* = 0.5\,\mu$as, while

$$\theta_{\rm E} = \sqrt{\kappa M \pi_{\rm rel}} = 0.45\,{\rm mas}\sqrt{\frac{M}{0.5\,M_\odot}\,\frac{\pi_{\rm rel}}{50\,\mu{\rm as}}} \tag{3.1}$$

where $M$ is the mass of the lens, $\pi_{\rm rel}$ is the lens-source relative parallax, and $\kappa = 4G/c^2{\rm AU} \sim 8.14\,{\rm mas\,yr^{-1}}$. Hence, for bulge lenses, the magnification generally cannot exceed about $A = 2000$. In this case, the source was blended with a foreground disk star that was most likely the lens. This foreground lens not only enabled the extreme magnification (through its high $\pi_{\rm rel}$), but also *initially disguised* the high magnification because it was about 50 times brighter than the source. With color information (which is not routinely taken), it would be possible to spot events with bright foreground lenses and so recognize in advance both their higher-than-apparent magnification and their potential for extreme magnification.

Finally, these high-magnification events are intrinsically more difficult to analyze than the more typical events anticipated by Gould & Loeb (1992). At the same time, their analysis is accessible to specialized techniques that take advantage of their high magnification. Subo's analysis of OGLE-2004-BLG-343 therefore paved the way for future detections.

## 4. OGLE-2005-BLG-071

The first fruit of this focus on high-magnification events was OGLE-2005-BLG-071 (Udalski et al. 2005). There were barely detectable deviations from a point-lens lightcurve on the night before peak, which led to very intensive observations the next night by both OGLE and $\mu$FUN Chile, but as Sun rose in Chile, the nature of the event was far from clear. Observations were taken over by the Auckland and Farm Cove telescopes (Grant and Jennie, respectively) in New Zealand. The triple-bump peak was then traced out over 4 nights by these and other telescopes (both from $\mu$FUN and other groups).

The event reached magnification $A = 65$. At the time this seemed to be "high-magnification" and we advertised this as the "first high-mag planet". In retrospect, however, $A = 65$ is really not very high, and while its sensitivity to planets is certainly greater than that of typical events, most of this sensitivity does not actually come from the central caustic (the feature emphasized by Griest & Safizedah 1998) but rather from the enlarged planetary caustic that Gould & Loeb (1992) already noted to be present in what we would now characterize as moderately high-mag events. In fact, the OGLE-2005-BLG-071 planet was detected via its central caustic, but this was only because this planet was huge: planet/star mass ratio $q = 0.007$. Such ratios are of course known from RV studies, but the planet frequency at these mass ratios is also known to be small. Judged by that standard, we were lucky: we had observed an event that was not high-mag enough to have good sensitivity to "regular planets", but by good fortune the lens happened to have a very big planet. But exactly how lucky we were could not be ascertained until the event was fully analyzed. This took several years of unexpectedly painstaking work.

### 4.1 Complete Analysis

There is actually a huge amount of information available on this event, some pretty well-defined (like parallax) and other fairly marginal. For example, finite source effects were detected at the $\Delta\chi^2 = 3$ level and source-lens relative motion was detected (by *HST* observations) at the $\Delta\chi^2 = 8$ level. Both of these measurements constrain $\theta_E$. In particular, even though the finite-source detection is quite weak, it provides strong *lower limits* on the $\theta_E$ (from the *lack* of pronounced finite-source effects). Stitching together these and several other types of data, Subo was able to constrain the mass of the host to the range $0.3M_\odot < M < 0.55M_\odot$ $(2\sigma)$ (Dong et al. 2008). This implies that the planet is $m_p = 3.4\,m_{\rm jup}$, by far the highest mass companion to an M-dwarf detected by any method. Indeed, it is so high as to call into question the core-accretion model, which predicts that low-mass stars should not have such high-mass planets. So, we were beyond lucky to detect it.

## 5. OGLE-2005-BLG-169

This was a truly high-mag event, $A = 800$, yet it was extremely difficult to recognize. It was only because we were putting a lot of resources into identifying high-mag events that we recognized it at all. OGLE did not observe this target for 6 days before the peak. In reconstructing this, I think that the first 4 days were due to bad weather and the last two were due to “Chile time”: Andrzej was at the telescope but was service observing for the Chileans, who get 10% of all time for telescopes in Chile. Based on the previous OGLE data, $\mu$FUN suspected that this event might become high-mag and obtained one point on each of the two nights before peak from $\mu$FUN SMARTS in Chile. From their 0.64 mag rise, these points remained consistent with a high-mag interpretation but did not convincingly prove it. I somewhat foolishly asked for only 4 points from $\mu$FUN SMARTS, but did have enough sense to ask Andrzej to sneak in one OGLE observation, which would instantly reveal whether the event was high mag. Andrzej sent me email at 3:54 AM (both Chile and Columbus times) noting that the event was extremely high-mag, but saying that he was unable to observe continuously because of Chile time. At this point, we also did not have override privileges at SMARTS (but see below), so I contacted Deokkeun An, an OSU student who happened to be observing at MDM in Arizona. Despite my rather cautious request that he observe it 3 times per hour over the next 3 hours, he instead took over 1000 observations, which is what enabled detection of the “cold Neptune” in this event (Gould et al. 2006).

This event also had a big impact on our thinking. First, it showed that we were far too cautious in acting on potential high-mag events, both in requesting intensive observations for something that might be high mag, and in requesting that other observers put aside their “normal” observations when an event is *known* to be high-mag. Second, we realized that we needed to be able to contact the SMARTS observer to do on-the-spot overrides when we had hard information of high magnification. In fact, once apprised of the situation, SMARTS PI Charles Bailyn was very willing to set up special protocols to permit this. Third, it became clearer that we needed some way to align OGLE and $\mu$FUN photometry other than through the lightcurve. This is a fairly technical, but very important, point.

In general, microlensing fits allow each observatory (and filter) two independent parameters, $f_s$ and $f_b$, the unmagnified source flux and the unlensed blended flux respectively. Obviously, then, there must be at least 3 points from an observatory before it can contribute any independent information. Moreover, if these points are on the rising part of the lightcurve, before much has happened, then they must be on 3 different nights so that they are at significantly different magnification. This is a pretty big burden, since it is usually quite difficult to recognize an event as interesting 3 days before peak. If the magnification is already reasonably high, then one can assume $Af_s \gg f_b$, and so get away with only two points. That is what we did for OGLE-2005-BLG-169 (although this would not have worked for OGLE-2004-BLG-343 because the blended flux was in fact enormous). Nevertheless, even with this assumption, the information was rather ambiguous. If we could have put $\mu$FUN photometry on the same zero-point with OGLE photometry by some mechanism other than lightcurve fitting, then we could have made a very good prediction of high-magnification with just 2 points (or even 1 point if we assumed that the blending differences in the two systems was negligible – as we could have in this case). Since OGLE and $\mu$FUN SMARTS use very similar $I$-band filters, this alignment could be done to better than 1% precision using common comparison stars. Unfortunately, however, even at this late date there is no system in place that would allow such comparison photometry.

A final lesson is that the interpretation of this event was far from trivial, and even getting sufficient focus on the event was nontrivial. From the beginning, it was clear that the MDM photometry showed small, but highly significant deviations from point-lens microlensing. However, I personally was not convinced that this deviation was planetary in nature, or even that it was not a data artifact. The event peaked on 1 May 2005 (just a week after the peak of OGLE-2005-BLG-071). Six week later, on 15 June, Nick Rattenbury sent me an email with a fit having planet with mass ratio $q = 4.4 \times 10^{-6}$, i.e., just 1.5 times the Earth/Sun value. I had some technical objections to this fit, but did made no serious effort to do better.

The next to weigh in on this was Ian Bond, who announced on 26 November that he had found two solutions, with mass ratios $q = 2.1 \times 10^{-5}$ and $q = 4.3 \times 10^{-5}$. Less than 24 hours later, Dave Bennett announced fits with $q = 7 \times 10^{-6}$, and 3 days later found that the minimum for this solution was actually closer to $q = 1 \times 10^{-5}$. At this point, it was far from clear whether these various results were all basically part of the same $\chi^2$ minimum (which would therefore have to be quite complex), or whether they were separate minima (in which case the $\chi^2$ surface as a whole must be very complex). Since the intense MDM data stream covered only the falling part of the lightcurve, the latter should have seemed more plausible, and turned out to be correct, but I don't think anyone made this argument at the time. Indeed, my own view was that systematics in the data remained a very plausible explanation for the anomaly. It was only at this point that I encouraged Subo to modify the code he had developed for OGLE-2004-BLG-343 so it could be applied to do a systematic parameter search for this event. This analysis showed that there were in fact many minima, which spanned more than a decade in $q$, with two of these minima (neither previously found) having a roughly equal $\chi^2$ that was significantly lower than all the rest, and with qualitatively similar solutions. The "smoking gun" that this was a microlensing anomaly and not a data artifact was the sharp change of slope (only visible once the point-lens model was subtracted out) in the MDM data, which is the characteristic signature of a caustic exit.

This brief history of the characterization of the anomaly in OGLE-2005-BLG-169 emphasizes that even recognizing genuine anomalies is nontrivial and that proper measurement of planet parameters, at least for high-magnification events, really does require (at least in some cases) systematic (i.e. blind) exploration of parameter space. As I will show below, this is certainly not always true, but since it is true in some cases, this "blind search" technology is crucial to our field.

## 6. OGLE-2006-BLG-109

The last event that I want to discuss in detail is OGLE-2006-BLG-109 (Gaudi et al. 2008). The analysis of the event is the subject of another paper in these proceedings. Here I want to focus on the issues of recognition and lightcurve coverage.

Like all the other events in which $\mu$FUN played a major role, this event was high-mag: $A_{\rm max} = 520$. Unlike the others, we initiated monitoring because it was *already* known to be anomalous: On 28 March, OGLE EEWS issued an anomaly alert: "Because short-lived, low amplitude anomalies can be a signature of a planetary companion to the lensing star (cf. OGLE-2005-BLG-390) follow-up observations of OGLE-2006-BLG-109 are strongly encouraged!", based on a deviation of just 8%. At this point, the source was actually *already* magnified by a factor 16, but because of heavy blending, it appeared to be magnified by just a factor 1.35. $\mu$FUN immediately (80 minutes following alert) obtained additional observations from MDM. These were too late for the anomaly, but did ultimately constrain its duration. Over the next few days, we obtained data from several sites, but only became obsessive about these observations as the event approached high-magnification. A crucial role was played by the observations over peak from Auckland and Farm Cove. It was Scott Gaudi's recognition that the initial anomaly combined with this exit implies a planet of Saturn mass ratio, that caused us to max out on post-peak observations. Scott had predicted another bump from this planet 4 days later. In fact, 8 hours later, observations from the Wise 1m in Israel revealed a new bump, which seemed to show that Scott's prediction was wrong. In fact, the bump, which was completed by OGLE and $\mu$FUN SMARTS observations a few hours later, was due to a new planet. In the end, 11 observatories contributed to characterizing this complex event, 7 from $\mu$FUN, plus OGLE, MOA, PLANET Tasmania, and RoboNET Canaries.

## 7. Sketch of the 2007 Season

Unfortunately, I cannot give too much detail of the 2007 season because I do not want to preempt articles that are in preparation.

One important aspect is that our network greatly expanded during this season. We now have stations in New Zealand (6), Australia (2), South Africa (1), Israel (1), Chile (2), US (3), and Tahiti (1). This expansion has made us more effective in obtaining dense coverage. However, we also work as aggressively as possible to engage other groups to intensively observe the events we have identified as promising.

Without going into detail, I will say that we obtained dense coverage over peak of 3 different events with peak magnification $A > 500$. Two of these 3 contained planets. Among all events for which we obtained dense coverage over peak in previous years, there were exactly two with magnifications $A > 500$, and both contained planets. This means that among these extreme microlensing events (EMEs), we are four for five! It is not easy to recognize these EMEs in advance, but they seem to be highly productive.

On the other hand, among all "high-mag" events that have not reached EME status (say $50 < A < 500$) we have only detected one planet. And there have actually been quite a few of these moderately high-mag events that we have monitored. In 2007 there were 4 with very good to excellent $\mu$FUN coverage. In 2006 there were 2, and in 2005 there were 3 (including OGLE-2005-BLG-071). That means, over the same period, we are 1 for 9 for these ($50 < A < 500$) events.

Finally, I note that 2007 was the first year we made extensive use of our $H$-band data. As mentioned, these data were routinely taken in parallel with $I$ (or occasionally $V$) observations, but were hardly ever used because they are usually lower S/N than the optical observations. However, they provided crucial information for two events in 2007 (one planetary, one non-planetary), and moreover enabled us to obtain $I-H$ source colors in the case of a few other events, which proved important to their analysis.

## 8. Conclusions

$\mu$FUN is coming into its stride. We are more able to recognize high-magnification events in real time and more able to cover them, partly because we are expanding coverage with many new observers, mostly amateurs, at many longitudes. We also have two professional sites from which we routinely acquire data (the CTIO SMARTS 1.3m in Chile, and the Korean robotic LOAO 1m at Mt. Lemmon, AZ) as well as two others that contribute at key times (the Wise 1m and the MDM 2.4m). To date, we have played a major role in 5 planet-bearing events. 4 of these 5 were EMEs, extreme microlensing events with $A > 500$. Only one EME with good data over its peak failed to produce a planet. On the other hand, only 1 out of 9 moderately-high magnification events ($50 < A < 500$) produced a planet.

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