Using the Supernova / Acceleration Probe (SNAP) to Search for Microlensing Events Towards the LMC

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**ABSTRACT**

Microlensing experiments today have a tantalizing result; they have detected an excess of microlensing events beyond what is expected from known stellar populations. These events could be due to a possible form of Halo dark matter. However, study of these events is limited by their small number and poor photometric precision. The SNAP satellite, which has been proposed to search for supernovae, would be an ideal instrument to search for microlensing events towards the LMC. Due in part to its larger mirror, and largely to its superb space-based seeing and low background, with a modest program SNAP will be able to detect $\sim 250$ microlensing events per year. In addition, SNAP will generate $\sim 16$ high quality events per year with $1\%$ photometric resolution. These data should break the microlensing degeneracy, and determine whether the events are indeed due to dark matter lenses in the Galactic Halo. Side benefits of such a program will include a never before equaled catalog of variable stars in the LMC. On of the most intriguing possibilities is a direct measurement of the distance to the LMC. Such a measurement will determine what is today the most uncertain rung on the distance ladder and thus lock down the Hubble constant.

**Subject headings:** Dark matter — Gravitational lensing

1. Introduction

The principal motive for creating microlensing searches was to search for dark matter in the form of discreet lumps, or MACHOs, by searching for microlensing towards the Magellanic Clouds. A major result of these experiments has been to show that the dark matter is not composed of objects with mass in the range $10^{-7} - 10^{-1} M_\odot$ (Alcock et al. 1998, Lasserre et al. 2000). The MACHO group has claimed an intriguing positive detection of lensing events significantly above that expected from known stellar populations. However, these events are difficult to interpret owing to the degeneracies inherent in microlensing: the sole observable in an event, its timescale, is a function of three parameters, the lens mass, its parallax, and its proper motion.

If the MACHO events are interpreted as being due to lenses which are part of the halo, then roughly $20\%$ of the mass of the halo has to be made of MACHOs with mass about $0.5 M_\odot$. This result would be quite significant, representing the first detection of a component of the Milky Way dark matter. If the MACHOs were baryonic, their mass suggests that they might be white dwarfs, an interpretation which has been strengthened by a possible detection of halo white dwarfs by Ibata

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et al. (1999) although their Hubble Deep Field proper motion survey is not consistent with larger ground-based proper motion surveys (Flynn et al. 2000). However, white dwarfs make poor dark matter candidates (Graff et al. 1999; Fields, Freese & Graff 1998, 2000), so there is a real chance that the microlensing experiments have detected a new non-baryonic dark matter candidate such as primordial black holes (Carr & Hawking 1974; Jedamzik 1997).

Microlensing’s ability to detect Halo dark matter will always be cast in doubt as long as the microlensing events could be due to a possible background. One possible background is a rare population of variable stars, hitherto unknown because their frequency is so low (\(\sim 10^{-8}\)). Some of the detected microlensing events have high signal-to-noise and so precisely follow the microlensing light curve that their interpretation is unambiguous. Other microlensing events are detected with less signal-to-noise. During the course of the microlensing experiments, a whole class of such stars was discovered and eliminated from the samples, the so-called “blue bumpers”. However, there may be other sorts of variable stars lurking in the H-R diagram. For example, the EROS group has shown that one star in the LMC had a bump in its light curve resembling sufficiently a microlensing curve to be classified as a microlensing event. Five years later, its light curve had a similar excursion, suggesting that at least this star is a variable.

Another possible background is a previously unknown population of ordinary stars acting as either sources or lenses, sometimes called “self lensing”. These stars would cause true microlensing, but would not indicate the presence of dark matter. Although severe constraints have been put on this hypothesis (Gyuk, Dalal & Griest 2000), it is still viable. Weinberg (2000) has suggested that the LMC could be distorted out of virial equilibrium by the tidal forcing of the Milky Way in such a manner as to have a large thickness (and thus a large microlensing optical depth) while still maintaining the low velocity dispersion measured by several groups, and reviewed by Gyuk, Dalal & Griest (2000). Graff et al. (2000) report a possible detection of such a population along the line of sight to the LMC. For a recent review of the interpretation of microlensing events, see Graff (2000).

In sum, microlensing experiments may have detected a possibly non-baryonic form of Dark Matter, making up a good fraction of the mass of the Milky Way halo. However, this claim cannot be verified until all possible background sources of events, such as previously unknown populations of variable stars and lensing due to ordinary stars have been eliminated.

A variety of ways have been proposed to break this degeneracy, which we shall review later in this paper. These techniques either require very high signal to noise events, to look for subtle deviations from the standard microlensing light curve, or they require many more events than have been detected; either to do meaningful statistical tests on the events, or to look for rare exotic events.

We will show that the proposed SNAP (Supernova / Acceleration Probe) satellite would be an ideal tool to search for microlensing towards the Large Magellanic Cloud, and perhaps towards the Small Magellanic Cloud. With a relatively small amount of observing time, it could detect orders of magnitude more events than the current ground-based experiments. In addition, it would generate a reasonable ensemble of high signal-to-noise events, which would eliminate all doubts that these events are indeed microlensing events, and allow them to be classified as Halo lenses or LMC lenses.

2. SNAP

Both microlensing searches and supernovae searches require similar telescopes that are used in similar manners since both experiments involve searching for a point-like object that gets brighter and then dims over the course of tens of days. In fact, the MACHO group has found detected supernovae to be a substantial background in their experiment (Alcock et al. 2000a) and their telescope has been used to search for supernovae (Reiss et al. 1998), while the EROS group has a supernova search program using their telescope (Hardin et al. 2000). In both types of experiment, a large field is sampled frequently, with a frequency of hours to weeks. The “new” image is subtracted from a reference field, and one looks for a point-like bright spot, which could be either due to a supernova, or the amplification of a microlensed star. In both types of experiments, a “trigger” allows detection of the event in real time, allowing
for further, more intensive study. The primary difference between the two types of experiments is that microlensing observations must be done towards fields rich in source stars with low background contamination, while supernova searches are best done towards deep galaxy-rich fields with few foreground objects.

The Supernova / Acceleration Probe (SNAP) is a proposed satellite-borne telescope designed specifically for the detection and high-precision observation of cosmological supernovae. Since searching for microlensing events is so similar to searching for supernovae, it is unsurprising that both the hardware and software capabilities of the SNAP program are ideally suited to microlensing. SNAP’s mission objectives require a large field imager, high signal-to-noise observations of point sources, frequent light-curve sampling, and suffer from telemetry and pointing constraints. In the following, what we describe as “SNAP” is based on a feasibility-study design (available at http://snap.lbl.gov). Ongoing design and trade studies will formalize (and perhaps modify) SNAP’s mission parameters. They should not, however, do so in a way that significantly changes the characteristics important for microlensing science.

SNAP’s wide field of view is provided by a one square-degree optical imager. It and the optical telescope assembly’s photon gathering capabilities are distilled concisely into Table 1, which gives the signal-to-noise obtained from 140 second exposures of point sources of differing magnitude. Note that the noise is dominated by the source itself and not background zodiacal light.

SNAP’s current design maintains a fixed single face directed towards the Sun; this constrains observing fields with full-time accessibility to be towards the ecliptic poles. Fortunately, however, the LMC is nearly at the South Ecliptic pole, with an ecliptic latitude of −85°. The SMC would be a bit more difficult, with an ecliptic latitude of −65°. The Galactic center could not be observed by SNAP under its current design since it is near the ecliptic.

A modest search for \( t_E \sim 20 – 100 \) day LMC microlensing events could be folded into or incorporated in the supernova search. Finer temporal resolution could be achieved with a more ambitious microlensing survey using more of SNAP’s observing resources.

3. SNAP’s ability to detect microlensing events

In this section, we will estimate how many events could be detected by a microlensing program involving SNAP. We will follow the optimal microlensing formalism developed by Gould (1999). This formalism assumes that the microlensing experiment will use image subtraction to find microlensing events even when the source star is not isolated in the field, sometimes known as “Pixel Lensing”. SNAP will be well suited for pixel lensing since the image subtraction technique will already be implemented for its supernova search program.

The number of microlensing events detected will depend on the strategy adopted by the microlensing experiment. For the purpose of this paper, we shall assume that SNAP takes images with exposures of 140 seconds (which can accommodate its current feasibility-study draft telemetry rate). Following this strategy, SNAP could image 120 deg\(^2\) of the LMC in 5.3 hours. The bulk of observations should be made in one filter. Occasional observations can be be made in other pass-bands to provide color information on variable stars.

SNAP fields will be directed towards both Ecliptic poles and revisited with a frequency of \( \sim 4 \) days. We will assume that while SNAP is pointed towards the South Ecliptic pole it will observe the entire LMC in addition to its supernova fields. This sampling frequency of four days is short compared to the typical measured Einstein Radius crossing time of 40 days and the shortest measured Einstein Radius crossing time of 18 days, so these events should be detected without much trouble. Additional target of opportunity time could be allocated for deeper, better time-sampled photometry and color measurements of particularly interesting microlensing events.

Following the Gould (1999) estimate, the number of microlensing events that can be detected with a particular \( \chi^2 \) significance level depends on the signal-to-noise ratio of individual observations, and on the number of stars in the field, which in turn depends on the luminosity function of the LMC and the surface brightness of the field in question. The signal-to-noise of the current gen-
eration of ground based experiments is severely limited by the crowding of several stars into their super-arcsecond seeing. With its larger mirror, and most importantly, with its superb space-based seeing, SNAP should easily achieve a signal-to-noise far in excess of MACHO or EROS, or even the proposed next generation experiment (Stubbs 1998). Furthermore, unencumbered by weather and the moon and covering every one of the 120 fields during each observing run, its efficiency, the fraction of microlensing events occurring which are actually detected, should be close to 100% as compared with less than 50% for the MACHO experiment (Alcock et al. 2000a) and less than 30% for the EROS experiment (Lasserre et al. 2000).

We estimate the expected number of microlensing events to be found by our proposed experiment by scaling from the ground-based “next generation” microlensing experiment proposed by Stubbs (1998) and whose detection rates were given in Figure 2 of Gould (1999). The majority of SNAP events will come close to the detection threshold (e.g. $R = 24.5$ for a conservative $S/N = 15$) where a 140 second SNAP exposure is equivalent to a 220 minute ground exposure at new moon\(^2\). From Gould (1999) this observing depth will produce $\sim 245$ events per year of current ground-based quality across the entire face of the LMC, factoring in the difference between theoretical and real MACHO events.

The ground based experiments frequently see microlensing in unresolved source stars. They interpret these events by using HST to count how many unresolved stars there are. SNAP too will measure microlensing in unresolved source stars, but HST followup will also be unable to resolve these stars. Interpretation of these SNAP events will require either modeling the LMC luminosity function or measuring the luminosity function with a better resolution telescope such as NGST.

In addition to the shear increase in quantity, SNAP will also provide a large sample of high quality events. An examination of Table 1 shows that under the campaign we propose, SNAP will have 1% photometric resolution on all events brighter than $V < 21$. Nearly all LMC events discovered to date by the ground-based experiments are at least this bright, thus, all of these events would be followed with 1% photometric resolution. Since SNAP would cover a larger fraction of the LMC than the ground based experiments under our test observation strategy, and since its efficiency would be higher, it would find roughly 4 times as many bright events as the MACHO collaboration finds (one factor of 2 coming from the higher efficiency, and one factor coming from the increased area of our proposed SNAP survey), or perhaps 10 bright events per year.

We can make a quantitative estimate of this number as follows: The detection rate of microlensing events is

$$\Gamma = \frac{2}{\pi} N_\star \frac{\tau \epsilon u_0}{t_E}$$

where $N_\star$ is the number of observed stars, $\tau$ is the optical depth, $\epsilon$ is the efficiency of detection, $u_0 \approx 1$ is the minimum impact parameter for an event to be classified a “detection”, and $t_E \approx 40$ days is the typical Einstein radius crossing time of the event. This method is applicable in the

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**Table 1**

**Signal to Noise for exposure of 140 sec**

| Filter | Magnitude  |
|--------|------------|
|        | 20 | 21 | 22 | 23 | 24 | 25 |
| V      | 135 | 85 | 53 | 32 | 19 | 10 |
| R      | 157 | 99 | 61 | 37 | 22 | 12 |
| I      | 128 | 80 | 49 | 29 | 16 | 8  |

\(^2\)At these magnitudes, SNAP is source noise dominated whereas the ground experiment is sky dominated; SNAP is thus faster by the ratio of sky (168 e\(^-\)/sec) and source fluxes (3 e\(^-\)/sec). Mirror apertures and quantum efficiencies give similar counts for the same source.
case where the source stars are not crowded, true for the brighter sample of stars under consideration here with the expected SNAP resolution. According to the MACHO collaboration (Alcock et al. 2000a), the optical depth towards the LMC is roughly $\tau \approx 10^{-7}$. Using the luminosity function of Alcock et al. (2000b), we see that there are roughly $N_* \approx 2.5 \times 10^7$ stars brighter than $V < 21$ in the LMC. Assuming that the efficiency of detecting such bright events is $\epsilon \approx 1$, we expect an event rate of 16 bright events per year.

4. How will SNAP data resolve the Microlensing Degeneracy?

There are several proposed techniques to determine whether the observed lensing is indeed due to lenses in the Halo. These techniques have heretofore been limited by the low quantity and quality of microlensing events. However, the two orders of magnitude increase in quantity of SNAP events, and order of magnitude increase in photometric precision will allow these techniques to come into their own.

As noted above, SNAP should detect some 16 events with 1% photometric resolution and occasional color measurements. If these events conform to microlensing lightcurves, there should be no further doubt that they are due to microlensing and not to some exotic unclassified variable star.

Gould (1998) suggested that if a typical LMC microlensing event is measured every day with 1% photometric resolution, then one could measure the leading term of its microlensing parallax (the mean acceleration of the earth) (Gould 1992), a small deviation from the standard microlensing light curve due to the motion of the earth around the sun. In that case, one can still not completely break the degeneracy of the microlensing event, but it should still be possible to separate halo lensing (which should have detectable parallax) from LMC lensing (which should not). This technique could only be applied to events brighter than $V < 21$ and as discussed above, SNAP should see $\sim 16$ of these events per year.

To measure the parallax of these 16 events, they should be followed up daily. Since only 4 of these events will be visible at any one time on average, this daily follow-up requires an additional 18 minutes per day on average. This follow-up need not be done with SNAP with its enormous field of view: with proper coordination, HST could serve instead.

The microlensing parallax signal scales as the square of the event time scale, so we would only be able to measure the parallax of the longer events. Thus, the parallax technique would not be sensitive to the possibility that, for some reason, the longer events are due to LMC self lensing while the shorter events are due to, e.g., brown dwarfs in the halo. Therefore, we note other methods SNAP will be able to use to break the microlensing degeneracy which will make use of the shear quantity of microlensing events detected by SNAP.

If the microlensing events are truly due to Halo lensing, then we would expect only a small change in the optical depth and time scales of microlensing events across the face of the LMC. The MACHO group (Alcock et al. 2000) has already used this technique to rule out one particular model of LMC self lensing, but has not ruled out all realistic models of self lensing, being hampered by the relatively low number of events in their sample, and by the limited spatial extent of their fields. The SNAP program, with its ability to detect hundreds of events across the face of the LMC, would be able to clearly rule out models of LMC self lensing.

In addition to being uniform across the face of the LMC, the optical depth must also be uniform across the H-R diagram. Zhao, Graff & Guhathakurta (2000) have suggested that under LMC self lensing models, the source stars will tend to be towards the back of the LMC. They should thus be somewhat more reddened and somewhat dimmer than the LMC field stars. The MACHO group has looked for this effect in their sample, but has been unable to draw firm conclusions owing to the relatively small number of events in their sample (Alcock et al. 2000c). Also, by verifying that the much larger sample of events are evenly drawn from the HR diagram, SNAP will confirm that the events are true microlensing events and not due to some heretofore unknown type of variable star.

By generating a large number of events, SNAP will generate a decent sample of rare events, such as finite source size events (Alcock et al. 1997), amplification of a binary source (Han & Gould 1997) or events due to a binary lens (Schneider & Weiss 1986). All of these variations on the stan-
Standard microlensing curve allow a partial breaking of the microlensing degeneracy, by uncovering one of the two hidden parameters, the parallax of the lens and its proper motion (relative to the source in both cases). Still, this partial breaking will be enough to simply distinguish between the Halo-lensing hypothesis and the self-lensing hypothesis, though it won’t be able to do finer measurements of, for example, the mass function of the lenses.

As shown by Honma (1999), high amplification events and binary lens events should be completely solvable if intensely monitored from a satellite such as SNAP by using the motion of the satellite as its orbit moves the satellite in and out of the caustic. The non-linear motion of the satellite as the satellite orbits the earth causes a small (1%) deviation in the shape of the light curve during the caustic crossing. This technique will only work if the caustic crossing time scale is about as long, or longer than the satellite orbit time, 7–14 days. Thus, the Honma technique can only be applied to events which are known to be self lensing events, which have much longer caustic crossing time scales than halo lensing events. Still, this technique, by directly solving the event, will resolve the mass function of the binary population of the LMC. That is, we will be sure of the mass of the components of the lens, whereas now, we have to estimate the mass of the lens statistically, and based on assumptions of the parallax and proper motions of the lenses.

In summary, SNAP will be able to break the microlensing degeneracy using several independent techniques, and thus unambiguously determine whether or not the lenses lie in the Halo or in the LMC. SNAP thus has the potential to identify a large component of the dark matter in the Galactic Halo.

5. Non-microlensing programs

In addition to the microlensing results from this LMC program, there will be other scientific results which may be just as interesting as the microlensing results themselves. It is beyond the scope of this work to detail them all, and we challenge the astronomical community, especially the experts in variable stars, to propose further benefits of these observations.

5.1. Variable stars

Microlensing surveys have already begun a revolution in the study of variable stars (e.g. Bauer et al. 1999, Alcock et al. 1999, Udalski et al. 1999). The two order of magnitude increase in depth and precision made possible by SNAP cannot help but increase the pace of this revolution.

The ground based microlensing experiments have been limited in their studies to relatively bright, high amplitude stars, such as Cepheids. SNAP will be able to generate similar catalogs of dimmer variable stars, such as δ Scuti stars, and of stars with low amplitudes, such as CP stars (Hensberge 1993). SNAP will also possibly discover new types of variable stars which had been missed in the past because they are rare and have small amplitudes.

There are too many types of variable stars to detail individually in this paper. However, we can lay out the general benefits of such a program that will apply to all types of variable stars.

All the variable stars found by SNAP will be at the same distance (to the extent that the LMC is thin), and with relatively low reddening, facilitating the construction of color magnitude diagrams of variables, perhaps yielding their mass, age, and metallicity. The efficiency of finding variable stars will be constant across the face of the LMC and well modeled; thus we will be able to characterize the frequency of variable stars. The high resolution of SNAP will find many variable stars in LMC clusters, allowing a measurement of their age. Perhaps most importantly, the LMC has a lower metallicity than the Milky Way, though the age and perhaps environments are similar, so studies of LMC variable stars will be able to examine the effect of metallicity on variable stars.

For all variables which are driven through internal pulsations, even those with low amplitude, SNAP will generate precise light curves. Studies of the detailed shapes of light curves of stars driven by internal pulsations will yield new measures of the internal structure of these stars.

5.2. Distance to the LMC

The distance to the LMC is at present the most uncertain rung in the cosmic distance ladder. Cepheids in the LMC are well studied (and will be even better studied by SNAP as discussed in
the previous section) and are used to calibrate the distance to other galaxies, which may in turn be used to calibrate other distance indicators. With a major campaign involving the Hubble Telescope, much of the traditional uncertainty surrounding the Hubble Constant has dissipated, to the extent that the reported values of the Hubble constant tend to vary within a narrower band than the factor of two common ten years ago. For example, Gibson et al. (2000) report a value of $H_0 = 68 \pm 2 \pm 4 \text{km s}^{-1}\text{Mpc}^{-1}$ while Saha et al. report a value of $H_0 = 60 \pm 2 \text{km s}^{-1}\text{Mpc}^{-1}$.

Both of these measurements assume that the distance to the LMC is 50 kpc, but the present day uncertainty of the distance to the LMC is larger than the reported uncertainties (which do not include the LMC distance), or than the difference between these two values. In contrast to the Hubble Constant, there continues to be disagreement over the distance to the LMC. This distance is usually measured with standard candles, lately normalized against local candles calibrated with Hipparcos. For example, Feast and Catchpole (1997) find a distance to the LMC of $55 \pm 2.5$ kpc using trigonometric parallaxes of Cepheids while Udalski (2000), using a variety of distance indicators, finds a value of 44 kpc.

By co-adding 100 images of the LMC, SNAP should in effect generate a total exposure of 14,000 seconds covering the entire LMC. This will generate an HR diagram containing 100 million stars measured with 1% photometric resolution, down to $V < 25$, or down to absolute magnitude of $M_V \sim 6.5$. This data set will allow a larger group of standard candles to be used to calibrate the LMC distance. The extra precision will also allow a study of the orientation and three dimensional structure of the LMC.

The most satisfying solution would be to directly measure the distance to the LMC. With such a detailed study of the LMC, and with such high resolution, it may be possible to directly measure the distance via trigonometric parallax. The ability of SNAP to measure parallax will be limited by its relative astrometric precision. For the moment, in this paper, we will discuss the purely statistical limits (due to photon noise, and a limited number of astrometric sources) to the astrometric precision.

The astrometric precision, especially in the case where the seeing is of order the pixel size (the $V$ band is undersampled for SNAP) will depend on the details of the point spread function and the detailed shape of the individual pixels. Given the possibility of dithering and the stability and planned study of the PSF, we can assume that the astrometric precision is roughly the seeing times the photometric uncertainty. Thus, for a single pointing towards a 20th mag star, SNAP should have an statistical astrometric precision of $\sim 1.5 \mu\text{as}$.

The more crowded LMC fields may have some $10^6$ stars as bright as magnitude 20, and we are interested in the average parallax of these stars. Hence, the astrometric precision may be limited by the number of distant astrometric references rather than by the number of foreground LMC stars. There are about 30 quasars brighter than magnitude 20 in each 1 degree square SNAP field, not enough to achieve the required statistical precision. Ibata et al. (1999) used compact bright galaxies as their reference. They found 50 in the 0.0015 deg$^2$ Hubble field of view, so there should be $\sim 3 \times 10^5$ in the SNAP field (roughly the same as the number of brighter stars).

With an exposure every 4 days for a period of 4 years, there will be 365 total exposures. Thus, the total statistical parallax precision towards the LMC is roughly

$$
\sigma_\pi \approx 0.14 \mu\text{as} \left( \frac{365 \times 10^5}{N_{\text{exp}} \times N_{\text{obj}}} \right)^{1/2}.
$$

This estimate of the parallax precision is about 0.6% of the parallax of the LMC, $20 \mu\text{as}$, compared to the present day uncertainty of about 20%.

This estimate only deals with the purely statistical uncertainties involved with such a program. This project will obviously be limited by systematic uncertainties, which cannot be estimated at this stage in the design of the satellite. These systematic errors may prove too large to be useful. Nonetheless, with such high statistical precision, it is worth pursuing such a program in the hopes that the systematic uncertainties can be beaten down to an interesting level.

6. Conclusion

We have shown that the SNAP satellite will have orders of magnitude greater sensitivity to mi-
crolensing events than ground-based searches. A relatively modest program, one which can be done concurrently with the primary mission of SNAP to search for supernovae, can cover the entire LMC and find $\sim 245$ events per year. This program should also find some 16 events per year with 1% photometric resolution. Armed with these data, it will be possible to identify the location of the lenses; are they in the galactic Halo or in the LMC?

Any microlensing program would also have several important side benefits, including a new variable star study of the LMC, and the construction of an extremely deep compendium of LMC stars. One novel side benefit may be a new precise direct measurement of the distance to the LMC, allowing a more accurate determination of the Hubble constant and extragalactic distance scale.

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