

# Microlensing in the Virgo Cluster and the Role of Baryonic Dark Matter in the Universe

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 Scientific category: DARK MATTER  
 Instruments: OPT/CAM, NIR/CAM  
 Days of observation: 5

## Abstract

We propose a microlensing monitoring campaign of the semi-resolved stellar population in M87 and other luminous galaxies in the Virgo cluster. If a fraction  $f$  of the cluster dark matter is in MACHOs of  $0.001 < M/M_{\odot} < 0.5$ , then  $\sim 5,000 f$  stars will be detectably magnified at any given epoch in each  $2.5' \times 2.5'$  field. If all the mass near M87's center is in stars, star – star lensing within M87 will contribute an additional event rate that is comparably as high for  $f = 0.1$ . By observing fields at different radii within M87, the contribution of intra-cluster MACHOs (ICM's) can be differentiated from star – star events. By observing different galaxies within the Virgo cluster the spatial distribution of the ICM's can be mapped out. As a result, this experiment will provide a comprehensive view of MACHO's in a cluster environment. In conjunction with the ongoing local group experiments, it will allow for the first time to probe whether baryonic dark matter provides at least a partial answer to what the universal dark matter is.

The program requires about daily monitoring ( $\sim 1000$  sec/field) over about a month. At a mean surface brightness of  $\mu_I = 19$  mag/asec<sup>2</sup> and a spatial resolution of  $0.03''$ , about 30 stars of the characteristic “fluctuation luminosity” ( $m_I \sim 30$ ) contribute to each resolution element, making magnification events of  $A - 1 \gtrsim 1.5$  detectable above the noise. Overall the project requires a facility that can (1) provide a spatial resolution of  $0.03''$  over a field-of-view that is  $\gtrsim 2' \times 2'$ , (2) an imaging depth of  $S/N \gtrsim 200$  at  $m_I = 25.5$ , and (3) a stable, or well known, PSF. NGST can satisfy all these requirements, but both HST and ground-based telescopes with AO fall short by orders of magnitude.

If a total of 10 fields are monitored, the overall exposure time required for NGST is about a hundred hours. Because the spatial distribution of the stars and their kinematics are well understood, the star – star lensing events can also be used as a strong constraint on the stellar mass function in elliptical galaxies.

ASWG DRM Proposal

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**Observing Summary:**

Target	RA	Dec	$K_{AB}$	Configuration/mode	Days
M87 AND OTHERS IN VIRGO	12h26m51.6s	+12d43m36		OPT/CAM or NIR/CAM	5
				Grand total days	5

## ■ Scientific Objectives

That the nature of the dark matter, which is the dominant constituent of our universe, is still completely unknown, may be the the most embarrassing puzzle in Astronomy. Recently, evidence has emerged that on Galactic scales, baryonic dark matter in the form of MACHOs (**MA**ssive **C**ompact **H**alo **O**bjects) is a part of the answer. Monitoring campaigns (Alcock et al. 1997) of the LMC have revealed instances where LMC stars have been magnified by the gravitational focusing of a mass which crossed very close to the line-of-sight. As the image splittings are only  $\sim 10^{-6}$  asec (“microlensing”), the only observable is the characteristic brightening and fading of the star. Currently it is estimated that between 10% and 80% of the mass column density between the Sun and the LMC may be in MACHOs, that have masses in the range  $0.001 < M/M_{\odot} < 1$  (Alcock et al 1997).

Most current approaches to microlensing search for the brightening of individual stars and therefore have to rely on resolved galaxies (within a few 100 kpc) as the background sources. Crofts (1992) has proposed to search for microlensing by monitoring the semi-resolved population of M31’s bulge (with a technique described below). Yet, even with these modified techniques, HST and ground-based 8 m class telescopes restrict the search for MACHO’s to the 1 Mpc surrounding the Milky Way, and precludes any test of the hypothesis that MACHO’s are a relevant part of the ubiquitous, and maybe universal, dark matter.

NGST, with its combination of high resolution ( $\sim 0.03$  asec) over a respectable field-of-view ( $\sim 2' \times 2'$ ) and imaging depth ( $m_I \approx 31.5$  at S/N=10 within an hour), provides a unique opportunity to extend microlensing experiments to at least Virgo cluster distances, opening up a representative portion of the local universe to stringent tests of its baryonic dark matter content.

We will detail the specific case where stars in bright bright Virgo galaxies (e.g. M87) are “microlensed” by potential intra-cluster MACHOs (ICM), which constitute a fraction  $f$  of the total cluster mass. This idea was first put forth for HST by Gould (1995), in a somewhat speculative and quite optimistic paper. Compared to the LMC experiments, the expected detection rate of microlensing events towards M87 is orders of magnitude higher for two main reasons: (1) optical depth to lensing through the Virgo is about 35 times higher than through the MW’s halo (owing to  $\tau \propto v_c^2$ ), and (2) “pixel lensing” (Crofts 1992, Gould 1996) can be applied to much more crowded fields (with 1 - 1000 stars per spatial resolution element), providing a vastly larger number of stars that could be lensed.

The idea behind “pixel lensing” is as follows (Crofts 1992, Gould 1996): at some distance from M87’s center (say, 1’), the flux from each NGST resolution element ( $0.03'' \times 0.03''$ ) arises from about 30 stars of the characteristic “fluctuation magnitude” (Tonry, 1991). This magnitude ( $M_I \sim -1.2$ , or  $m_I = 29.8$  at M87’s distance) comes from a proper average over the galaxies stellar luminosity function. If one of these stars were magnified to a factor of  $A = 4$ , the flux from this resolution element would increase by 10%, which is detectable at the  $10 \sigma$  level, for a S/N=100 per resolution element. If a time sequence of images is available, including a “base-line” from a disjoint epoch, the series of difference images gives the pseudo-lightcurve,  $A(t) - 1$ , without requiring photometry of individual stars. The

statistics of such pseudo-lightcurves can then be converted to optical depth estimates, and ultimately to the fraction of dark matter that is in MACHO's.

At any given epoch the number of stars within a field-of-view,  $\Omega_{CCD}$ , that are detectably magnified,  $A > A_{min}$ , is given by the product of (1) the magnification probability per star,  $\tau(> A_{min}) \approx 10^{-5} \cdot f$  for M87, (2) the effective number of "fluctuation magnitude" stars ( $m_I \approx 30$ ) per resolution element,  $N_* \approx 30$ , and (3) the number of resolution elements across the F.O.V.,  $\frac{\Omega_{CCD}}{\Omega_{PSF}}$ , which is approximately  $1.6 \cdot 10^7$ , for a  $8k \times 8k$  detector array and  $\Omega_{PSF} = 4$  pixels. The characteristic event durations are  $2 \sqrt{M_{ICM}/M_{\odot}}$  weeks. For a S/N=250 per resolution element (see below for feasibility), the minimal magnification for a characteristic star is  $A_{min} \approx 2.5$ .

Multiplying all these factors together, it is found that at any epoch  $5,000 \cdot f$  will be detectable within one field of view. Hence a month-long monitoring campaign of a field (requiring  $30 \times 20$  min, or 10 hours of total exposure time, see below) would detect several hundred lensing events even for MACHO mass-fractions well below 10%. As the stellar mass column density near M87's center is comparable to the cluster's dark matter column, we should expect a significant rate of star – star lensing (the rate is equal at M87's center for a ICM mass fraction of  $f = 0.1$ ; Gould 1995). These two processes can be distinguished, as the star – star rate should fall off as the square of the stellar surface brightness, while the ICM rate should stay nearly constant on  $\sim 10$  kpc scales. As the spatial distribution and kinematics of M87's stars are well understood, the frequency and even duration distribution of star – star lensing can be used to probe the low mass end of the stellar mass function in this giant elliptical galaxy. The ICMs, should they exist, can be mapped out by looking at different galaxies in the Virgo cluster.

Monitoring 3 different fields each in M87 and a few other galaxies (at differing galactocentric distances), suggest that a total of 10-15 fields.

Alcock, C., et al., 1997, ApJ, 486, 697.

Crotts, A., 1992, ApJL, 399, 43.

Gould, A., 1995, ApJ, 455, 44.

Gould, A., 1996, ApJ, 470, 201.

Tonry, J., 1991, ApJL, 373, 1.

## ■ NGST Uniqueness/Relationship to Other Facilities

As the experiment tries to detect the magnification of faint stars ( $m_I \sim 30$ ) against the background of all other stars within their spatial resolution element ( $N_* \gtrsim 10^4 \times \frac{\Omega_{PSF}}{asec^2}$ ) it requires

- High spatial resolution  $\lesssim 0.03$  asec<sup>2</sup>.

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- Great imaging depth,  $S/N \gtrsim 200$  for  $m_I = 26$ .
- Stable PSF.
- Significant field of view,  $\sim 2' \times 2'$ .

In return, the experiment can decide whether baryonic dark matter (MACHO's) play a generic role as dark matter on galaxy and cluster scales. NGST can deliver this combination of requirements, all other set-ups fall hopelessly short: HST is lacking both lacking the photon collecting power and the resolution: the experiment's time requirement for diffraction limited imaging decreases with increasing aperture as  $D^{-4}$ , and it would take more than a hundred times longer to carry out the experiment with HST. Even then HST would only detect "spike" events that contain less information (G95). Ground-based telescopes with AO (at  $\lesssim 1\mu\text{m}$ ), lack both the field of view and the stable PSF that is required.

As mentioned, the project aims at detecting the amplification of "typical giant stars ( $M_I \sim -1.2$ , or  $m_I = 29.8$  at Virgo's distance) by factors of  $\gtrsim 2.5$ . Therefore the star's magnitude change must increase the flux within a resolution element by a detectable amount. At a surface brightness of  $\mu_I \approx 19$  mag/asec<sup>2</sup>, each resolution element of NGST (assumed to be  $1.5 \cdot 10^{-3}$  asec<sup>2</sup>) has a brightness  $m_I = 26$  mag, which arises from  $\sim 30$  stars of the "fluctuation magnitude,"  $m_I = 29.8$ . For a S/N per resolution element  $\Omega_{PSF}$  of  $\sim 250$  at  $\mu_I \approx 19$  (achieved over the time sequence of exposures), a 2.5-fold magnification of a "fluctuation magnitude" star would yield a  $10 \sigma$  detection of the lensing event. With NGST this requires a total exposure time of  $\sim 10,000$  seconds. The chance for any given star to be amplified by this amount is about  $\sim 10^{-5} \cdot f$ . For an  $8k \times 8k$  detector, sampling a  $0.03$  asec PSF at  $0.02$  asec/pixel, there are  $\sim 1.5 \cdot 10^7$  resolution elements. Each of these elements contains about 30 stars that each have a  $\sim 10^{-5} \cdot f$  chance of being detectably amplified, totaling  $\sim 5,000 \cdot f$  stars per F.O.V.

## ■ Observing Strategy

The characteristic event durations for ICM's of  $10^{-3}$  to  $10^{-0.5} M_\odot$  range from days to weeks (G95). If each of the ten fields in Virgo is imaged once a day for 1000 seconds over 30 days, sufficient S/N per resolution element is achieved along with appropriate time sampling. The fields will be within a few degrees of each other, requiring little slewing. The total time required 3 hours a day for a month, or  $\sim 100$  hours.

## ■ Special Requirements

Maximum FWHM:	30 mas at 0.5-1.3 $\mu\text{m}$
Minimum FOV:	1.5' at 0.5-1.3 $\mu\text{m}$
RMS offset accuracy:	10 mas
RMS repointing accuracy:	10 mas
Minimum precision/pixel dynamic range:	10000

## ■ Precursor/Supporting Observations