# A MICROLENSING SEARCH FOR COLD MOLECULAR CLOUDS IN VIRGO

H. TADROS
*Department of Physics, Astrophysics, Keble Road,*
*Oxford OX1 3RH, UK*

S. J. WARREN
*Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Rd, London, SW7 2BW, UK*

P. C. HEWETT
*Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA, UK*

We report preliminary results from a first season of photometric monitoring of 600 quasars behind the Virgo galaxy cluster with the aim of detecting microlensing by the cluster dark matter. Our project is sensitive to dark objects of surface mass densities down to $\sim 20\,\mathrm{g\ cm^{-2}}$. We are thus capable of detecting diffuse objects, such as cold molecular clouds, unlike all Galactic microlensing surveys whose surface mass density limits are $> 10^4\ \mathrm{g\ cm^{-2}}$. The average optical depth to microlensing of quasars through the central 30 sq. deg. of Virgo is $\sim 1 \times 10^{-3}$. We report a null detection which implies that less than half the dark matter in Virgo is in objects of mass $\sim 10^{-5}$ solar masses, of surface mass density $> 20\,\mathrm{g\ cm^{-2}}$, at $90\%$ confidence.

## 1 Rationale

The number of microlensing surveys underway is growing rapidly. Most of these surveys aim to detect compact objects in the dark halo of our own Galaxy or in the nearby M31 halo by monitoring stars in the LMC, SMC, or M31 itself. These projects have proved very fruitful detecting and placing limits on the dark matter in the Galaxy halo. The latest results indicate that less than $20\%$ of the Galaxy halo is in the form of MACHOs (see refs 1 and 2). There are, however, a number of shortcomings of the current surveys. Firstly, one cannot measure the distance to the MACHO and there is currently some controversy over whether the events seen towards the LMC are due to Galactic dark matter at all. Secondly, the objects have to be extremely compact to produce a microlensing effect at the distance of the LMC. Hence, current surveys provide no constraint on the hypothesis that the dark matter is composed of diffuse cold molecular hydrogen clouds (see e.g. refs 3 and 4). Thirdly, source blending greatly complicates the calculation of survey efficiencies.

We have begun a project which addresses these issues and provides completely new information on the nature of dark matter in galaxy clusters. We are monitoring 645 quasar candidates behind the Virgo galaxy cluster in order to detect dark objects in the cluster in the mass range $5 \times 10^{-7}\,M_\odot - 5 \times 10^{-3}\,M_\odot$ . The upper mass limit is set by the length of the monitoring program and the lower limit by the frequency of the monitoring. Quasar source size can also have an effect on the lower mass limit. If the quasar's angular size is larger than the angular

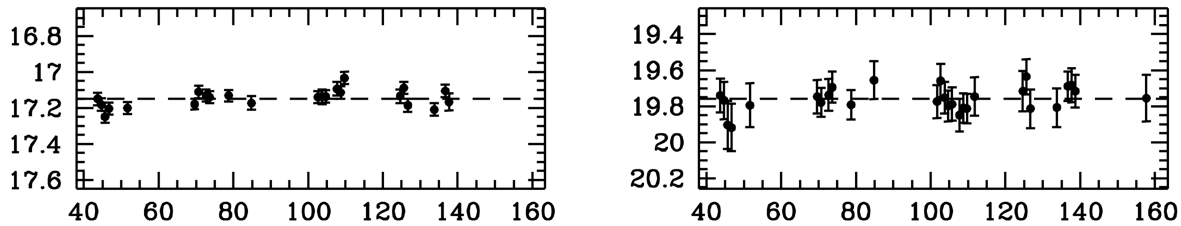


Figure 1: Typical light curves for quasar candidates monitored over a period of 113 days, plotting R mag. against 1999 day.

diameter of the Einstein ring of the lens, the magnification drops significantly and the event would not be detected. If all the mass in the Virgo cluster were in dark objects within the above mass range then we can expect to see significant numbers of microlensing events during our monitoring program (see ref 5 for details).

Several features of our monitoring program deserve to be emphasised. Firstly, if we see a microlensing event we have a reasonably accurate measure of the distance to the MACHO, allowing us to calculate its mass. Secondly, we can detect objects down to surface mass densities of a few tens of $\mathrm{g\,cm^{-2}}$ as these would act as point mass lenses when placed in Virgo. Such objects, for example cold molecular gas clouds, are accessible to no other current microlensing survey. Thirdly, because we are monitoring $\sim 600$ objects over a 30 sq. deg. field, we do not have blending of source images and the associated problems that blending causes.

One potential worry for a survey such as ours is the fact that quasars are intrinsically variable. If quasar variability is large on the time scales over which we are monitoring we would have to set our microlensing magnification threshold so high that the expected number of events would become very low. To date, little systematic quasar monitoring has been carried out on time scales matching those of our project, thus we have been careful to examine the feasibility of our project. As reported in this article, our pilot project proves that intrinsic quasar variability is not a serious problem on these time scales. A by-product of this microlensing survey is the information provided on the variability of quasars over these timescales, which will lead to constraints on models of quasar fuelling mechanisms.

## 2 Observations and data analysis

During the period 1999 February - June we obtained 28 R-band Schmidt plates of the central 30 sq. deg. of the Virgo cluster. The data are complete to an R-band magnitude of $20$. Using previous plates of the same area in the U and B bands we identified $645$ candidate quasars according to their colour. Of these we expect $\lesssim 10\%$ to be contaminant stars. Figure 1 shows $2$ typical quasar light curves extracted from this data set.

It can be seen qualitatively that the quasar candidates vary little during the monitoring period. We have quantified this by comparing the level of variability in the quasar candidates with the variability of $3000$ stars in our field. The candidate quasars are statistically no more variable than the stars. This confirms the feasibility of using quasars for microlensing surveys for monitoring periods of a few months. Our simulations show that with this low level of variability we can set a low detection threshold, and identify microlensing events down to a peak magnification of 0.46 mag.

We have run a matched filter analysis on each of the $645$ candidate-quasar light curves. The filter used was a MACHO light curve of peak amplification $0.6$ mag. We used a range of values for the event time-scale and the time of peak magnification. For each quasar light curve the event with the highest $\Delta\chi^2$ for a match to a MACHO event was retained. To this best event for

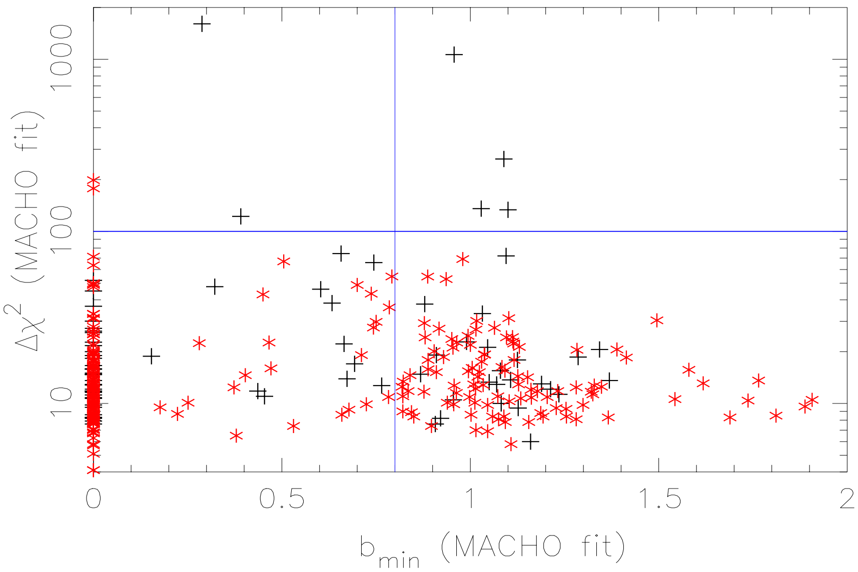


Figure 2: Plot illustrating microlensing candidate selection. For the best fitting MACHO event in each quasar (crosses) and star (asterisks) light curve we plot the $\Delta\chi^2$ against the fitted impact parameter. Our candidate selection criteria, $\Delta\chi^2 > 100$, $b_{min} < 0.8$, are designed to exclude all events in the stellar light curves (where we expect no real microlensing events).

each quasar, we performed a four parameter MACHO light curve fit.

To define selection criteria to pick out likely lensing events, we ran the same set of procedures on the light curves of the 3000 control stars in the field – where we do not expect any real microlensing events. Figure 2 shows the distribution of points in the plane of $\Delta\chi^2$ for the four parameter MACHO fit against the fitted impact parameter $b_{min}$. Quasar candidates are shown by crosses and stars as stars. We define the following criteria for an event to be considered as a serious microlensing candidate:

- $\Delta\chi^2 > 100$
- Impact parameter $b_{min} < 0.8$

These criteria leave two events in the candidate region to be checked. Neither of these proved to be real events: one is a known highly variable BL Lac object and the other a probable stellar RR Lyrae contaminant. From this null detection we can now put constraints on the nature of dark matter in Virgo.

## 3 Detection Efficiency and Predicted Number of Events

To calculate the detection efficiency of the survey we have generated artificial microlensing events and added them to the 3000 stellar light curves. For each event time-scale we have generated $10,000$ artificial light curves with impact parameters distributed uniformly between $0$ and $1$ Einstein ring radius and added them to the stellar light curves, placed at random dates. We then applied our matched filter analysis, the fitting routine, and the selection criteria to these artificial light curves and measured how many of the artificial events were recovered. Our detection efficiency is shown as a function of event time-scale on the left hand side of Figure 3.

Using the detection efficiency we can calculate the number of microlensing events we would expect to see in our experiment if the dark matter in Virgo were in the form of dark objects of a particular mass. We assume that the Virgo cluster can be modelled as an isothermal sphere with a one-dimensional velocity dispersion of $673\,\mathrm{km\,s^{-1}}$. Our expected number of

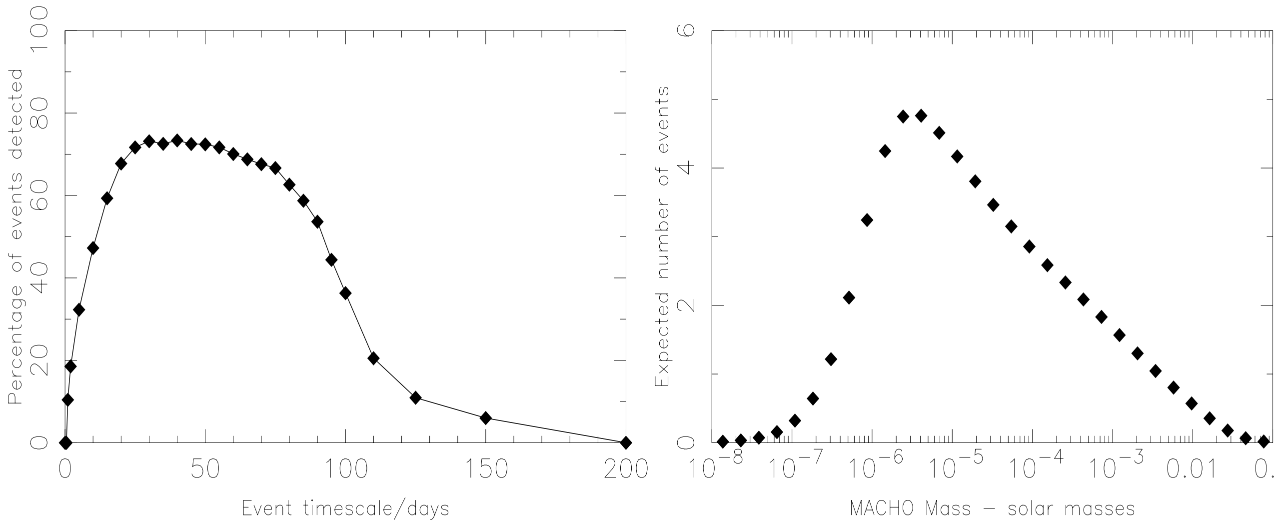


Figure 3: The left hand side of the figure shows the detection efficiency of our microlensing experiment as a function of MACHO event time-scale. The right hand side shows the expected number of MACHO events as a function of mass, assuming that all of Virgo is composed of objects of that given mass.

events is shown on the right hand side of Figure 3 and peaks at $5$, if all the dark mass in Virgo were in the form of $10^{-5}M_\odot$ objects.

## 4 Conclusions and future work

From our null detection, and the fact that we would have expected $5$ events for lenses of mass $1 \times 10^{-5}$ $M_\odot$ , we can use Poisson statistics to put constraints on the mass in Virgo in the form of dark objects of this mass. The result of this pilot project is that less than $1/2$ the mass in Virgo can be in the form of $10^{-5}$ $M_\odot$ objects at $90\%$ confidence.

The most important thing we have learnt from the pilot project is that a quasar monitoring microlensing project is technically feasible and we hope, over the next 2 years, to acquire of order $100$ more plates of Virgo. Our simulations indicate that this will allow us to improve our constraints on the nature of dark matter in Virgo by a factor $5 - 10$. A second season of monitoring Virgo started in February 2000.

We would also like to extend the experiment by monitoring other clusters - especially the Perseus cluster in the North as this is the most massive nearby cluster. Alternatively, another strategy would be to monitor several more distant clusters (thereby avoiding the need for a very wide field of view). In the long term we would also like to monitor a control field of quasars with no intervening massive cluster in order to precisely quantify quasar variability.

## Acknowledgements

We are immensely grateful to the Schmidt observing team: Fred Watson, Malcolm Hartley, Russell Cannon, Paul Cass, Ken Russell and Delphine Roussiel for taking all the photographic plates of Virgo used in this analysis.

## References

1. C. Alcock *et al.* 2000, *preprint:* astro-ph/0001272
2. T. Lasserre *et al.* 2000, *preprint:* astro-ph/0002253
3. M. Walker & M. Wardle 1998, *ApJ.* , **498**, L125

4. D. W. Sciama, 2000, *MNRAS* , **312**, 33
5. H. Tadros, S. J. Warren & P. C. Hewett 1998, New Astronomy Reviews, **42**, 115