How to find MACHOs in the Virgo Cluster

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Abstract

We discuss the feasibility of finding extra-galactic MACHOs by monitoring quasars behind the Virgo cluster of galaxies. We show that with only a modest observing programme one could detect several MACHOs in the mass range $1 \times 10^{-5} - 2 \times 10^{-2} \, M_\odot$ if they make a significant contribution to the mass of Virgo. The contamination by events from cosmologically distributed MACHOs is estimated and is negligible if either the MACHO mass is $\gtrsim 10^{-4} \, M_\odot$ or the quasar radius is $\gtrsim 3 \times 10^{15} \, \text{cm}$.

Key words: dark matter — galaxies: clusters: general — gravitational lensing — quasars: general

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1 Introduction

The optical depth to microlensing toward the LMC is a few $\times 10^{-7}$ and the detection of halo microlensing events requires extensive monitoring campaigns. The MACHO project, for example, after monitoring several million stars over a 2.3 year period reported only 8 events towards the LMC. In this article we discuss a search for MACHOs in the Virgo cluster, based on the microlensing of background quasars. As shown below the mean optical depth over the central 10 deg\textsuperscript{2} degrees of Virgo is $\sim 2 \times 10^{-3}$. Therefore one need monitor only hundreds of background quasars — compared with millions of stars in the LMC. For a relatively small investment in telescope time it is possible to obtain important new information on the nature of dark matter in rich clusters.

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2 The Optical Depth to Microlensing in Virgo

The case for microlensing searches in clusters was first made in an excellent paper by Walker & Ireland (1995). In this section we calculate the optical depth to microlensing of background quasars through the Virgo cluster. The motivation for choosing Virgo is explained below. We assume that Virgo can be modelled as an isothermal sphere of 1-D velocity dispersion $\sigma_{1D} = 670 \text{ km s}^{-1}$ (Danese et al. 1980). The effect of the core radius can be neglected. The quasars (e.g. at $z \sim 1$) are much more distant than Virgo (at 16 Mpc) and in this limit $D_s \gg D_d$ the optical depth at angle $\theta$ (in degrees) from the line of sight to the cluster centre is given by $\tau = \frac{360 \sigma_{1D}^2}{\theta c^2} = 1.8 \times 10^{-3}/\theta$. Therefore the average optical depth over the central 10 square degrees of the Virgo cluster is $\sim 2.0 \times 10^{-3}$.

3 The effect of source size

We now calculate the effect of finite source size. Walker & Ireland (1995) appear to have plotted this incorrectly (their Figure 3) and this has consequences for the optimal observing strategy. Here we suppose that once the radius of the Einstein ring (projected in the source plane) is less than half the quasar radius microlensing events will be undetectable since the light curve will be severely distorted relative to the point–mass approximation, and the maximum amplification, for perfect alignment, is $< \sqrt{2}$. The typical size of the continuum–emitting region in a quasar is still not well known. Theoretical considerations (Rees 1984) and one observational measurement (Wambsganss et al. 1990) suggest that quasar radii lie in the range $10^{14} - 10^{16} \text{ cm}$, corresponding to $3-30$ Schwarzschild radii for black–hole masses from $10^8-10^9 \text{ M}_\odot$.

We consider now a 150–day programme of nightly monitoring of quasars behind a massive cluster of velocity dispersion equal to that of the Virgo cluster. Figure 1 plots the range of MACHO masses detectable in such a survey as a function of redshift of the cluster. We assume a typical transverse MACHO velocity of $\sqrt{2}\sigma_{1D}$. The shaded regions are inaccessible because we would not see light curves with time-scales longer than $\sim 100$ days or shorter than $\sim 2$ days. The solid lines with the arrows show the constraints introduced by the size of the quasar for three possible quasar radii. For a given radius regions below the line are excluded. It can be seen that as the redshift of the cluster increases the accessible range of MACHO mass is squeezed: from above by the duration of the survey, and from below by the quasar source size. At lower redshifts the effect of finite source size is minimised, so we want to target the nearest massive cluster in order to maximise the range of masses detectable. This is the reason for choosing Virgo, as well as the fact that higher masses
Fig. 1. Plot showing the range of MACHO masses to which our example programme (as specified in the text) is sensitive. The shaded regions are excluded by the length of the monitoring programme. For a given quasar size regions below the solid lines are excluded due to the effect of finite source size. The curve marked 100 days background is discussed in §4.

are reached. If quasar radii are $< 3 \times 10^{15} \text{cm}$ we could detect MACHOs in the mass range $1 \times 10^{-5} - 2 \times 10^{-2} \text{M}_\odot$. The other suitable target is the Perseus cluster ($z = 0.018$, $\sigma_{1D} = 1010$). The optical depth through Perseus is more than twice as large as through Virgo, at the expense of a smaller range of masses explored.

We plan to monitor quasars brighter than $R = 20.3$ at which point the surface density of quasars is 30 deg$^{-2}$. Therefore we will obtain light curves for about 300 quasars and the probability that a microlensing event is taking place at any one time is $0.60 \alpha$ where $\alpha$ is the fraction of the mass of the cluster in MACHOs. If all the dark matter were in MACHOs of mass $1 \times 10^{-5} \text{M}_\odot$ (corresponding to the shortest observable time-scale of $\sim 2$ days) we would expect to see $0.60 \times 150/2 = 45$ events. If the typical MACHO mass were $2 \times 10^{-2} \text{M}_\odot$ (corresponding to the longest observable time-scale of $\sim 100$ days) we would see $0.60 \times 150/100 \sim 1$ event. Thus in 150 days we could measure or place interesting limits on the fraction of the mass of Virgo in MACHOs, over a mass range of over 3 orders of magnitude.

4 Contamination by cosmologically-distributed MACHOs

Another important issue is the likely contamination by events due to foreground and background MACHOs. If a substantial fraction of the mass of
Virgo is in MACHOs the same is presumably true on cosmological scales. Nevertheless the velocity dispersion of the cosmologically–distributed MACHOs will be much less than that for Virgo. We will assume $\sigma_{1D} = 200$ km s$^{-1}$ for 'field' MACHOs. The detection limit corresponding to a 100–day event is plotted as the dashed line in Figure 1, so that field MACHOs above this line will not be detected. The same is true of field MACHOs lying below whichever is the correct quasar–limit line. We see that field MACHOs can be found out to a limiting redshift $z_{\text{lim}}$, where $z_{\text{lim}}$ is the redshift where a horizontal line (for that mass) first cuts one of these detection limits. The optical depth to microlensing for cosmological compact objects is $\sim \Omega_M z_{\text{lim}}^2/4$ for $z_{\text{lim}} \ll 1$ (Press & Gunn 1973) so that the optical depth can be computed as a function of MACHO mass, for different quasar source sizes and different values of the cosmological density in MACHOs $\Omega_M$. For example suppose that $\Omega_M = 0.2$. We find that if the MACHO mass is $\gtrsim 10^{-4}$ the optical depth of field MACHOs is less than 10% of the average optical depth through Virgo, regardless of the quasar size. Field MACHOs are similarly irrelevant if the quasar radii are $\gtrsim 3 \times 10^{15}$ cm, regardless of MACHO mass. On the other hand for masses less than $\sim 10^{-4}$ if the linear sizes of quasars are much less than $1 \times 10^{15}$cm then we may have an appreciable cosmological background of events.

5 Further remarks

Besides the large optical depth there are several other advantages to using clusters as the target for microlensing searches. Firstly, the mass of the lensing object will be better constrained than in existing microlensing searches as the distance to the lens is known (although see §4). Secondly one avoids the problem of blending of the sources which complicates the current microlensing searches. The intrinsic variability of the background quasars is relevant, but should not be a serious problem as most optical quasars show only modest variability on the time-scales – a few days to a few months – in which we are interested (Hook et al. 1997). The $rms$ intrinsic magnitude variation of a quasar over a period of $\sim 3$ months is 0.09 mag, (Warren et al. 1994), while we will be looking for magnifications of $> 0.3$ mag. In any case it is the one-off nature and the characteristic time profile of microlensing events which are their signature and which will be the primary means of distinguishing between microlensing and intrinsic variability.

We have shown how it is feasible to obtain direct limits on, or make detections of, extra-galactic compact baryonic dark matter. Currently we are only able to probe the nature of this type of dark matter on scales corresponding to the Galaxy halo (of order tens of kpc). A project such as the one described here would obtain information on the nature of dark matter on scales of order 1Mpc. We plan to modify the observing strategy to make it suitable for use
with the INT wide field camera. To quantify our selection effects we also plan
to make a detailed study of the effects of intrinsic quasar variability on the
detection efficiency of MACHOs as a function of mass (Tadros, Hewett and
Warren in prep.).

**Question from Dr. Mike Hawkins:** Given that there are probably ways of dis-
tinguishing intrinsic variation from microlensing, how would you separate mi-
crolensing in the Virgo cluster from more general microlensing along the line
of sight to the quasars.

**Answer**
This is an important issue and the question prompted us to quantify the con-
tamination due to cosmological MACHOs (see §4). The expected background
event rate depends critically on the quasar size. It should be possible to deter-
mine whether we are primarily monitoring events in Virgo or more generally
along the line of sight from a combination of (a) the statistical distribution
of events over the field of view and by comparison with a control field, (b)
an examination of the timescales, (c) the possible measurement of the quasar
sizes in events which show flat–topped light curves, because the source angular
size is comparable to the Einstein angle. Of course one is just using Virgo as
a convenient testing ground, and we would like to know the nature of dark
matter throughout the Universe. Detection of MACHOs outside of the Virgo
cluster is therefore of great importance.

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