What Could the Machos Be?\textsuperscript{1}

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Abstract. If the Universe has a significant baryonic dark component in the form of compact objects in galaxy halos (machos), then there is a minute chance (about $10^{-7}$) that one of the Galactic machos passes sufficiently close to our line of sight to a star out of some $10^7$ monitored stars in the Magellanic Clouds (MCs) that it brightens by more than 0.3 magnitude due to gravitational focusing. After a brief discussion of the current controversy over the interpretation of the observed events, i.e., whether the lensing is caused by halo white dwarfs or machos in general or by stars in various observed or hypothesized structures of the Clouds and the Galaxy, I propose a few observations to put ideas of the pro-macho camp and the pro-star camp to test. In particular, I propose a radial velocity survey towards the MCs.

Current Debate. Experimental searches for microlenses in the line of sight to the MCs by MACHO, OGLE, EROS and a number of follow-up surveys have found more than 16 candidates to the LMC and two to the SMC. Most of them are clustered within 2° of the center of the LMC (cf. upper left panel of Fig.1). The observed rate falls short of explaining the rotation curve of the Galaxy with a smooth halo of machos (Alcock et al. 1997a). Whether this is yet another major puzzle in astronomy which requires explanation by fine tuning is an open question (Adams & Laughlin 1996, Chabrier et al. 1996, Charlot & Silk 1995, Flynn et al. 1996, Graff & Freese 1996, Gates et al. 1998, Gibson & Mould 1997, Honma & Kan-Ya 1998). Another complication to the otherwise plausible conversion of the event rate to $\Omega_{\text{macho}}$ of the Universe is the inevitable background events, on top of any macho signal, coming from lensing of two stars in the LMC disc (Sahu 1994). Since disc-disc lensing is not very efficient if the LMC disc is cold and thin (Gould 1994, Wu 1994), more speculative models have been put forward by the pro-star camp to boost up the star-star lensing by hypothesizing a variety of special structures to the MCs. In particular, a connection is drawn between the unexpected rate of microlensing and the Milky Way-MCs and SMC-LMC interactions (Zhao 1998a, b, Weinberg 1998); the latter is yet another long-standing issue, rooted in the tidal vs. ram-stripping formation of the Magellanic stream, which is resolved finally by recent

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observations (Putman et al. 1998 and references therein). Several observations and theoretical arguments suggest that our line of sight to the LMC passes through a 3-dimensional stellar distribution more extended in the line of sight than a simple thin disc of the LMC (Evans et al. 1998, Kunkel et al. 1997, Zaritsky et al. 1997, 1999, Zhao 1996). Others argue against additional structures other than the thin disc of the LMC (Alcock et al. 1997b, Gallart 1998, Beaulieu & Sackett 1998, Bennett 1998, Gould 1998, Johnston 1998, Ibata et al. 1999). The related issue on the efficiency of self-lensing of a tidally stretched SMC bar has also been brought up a few times (Alcock et al. 1997c, Palanque-Delabrouille et al. 1998, Zhao 1998a), but was highlighted soon after the discovery of the 98-SMC-1 caustic binary event (Afonso et al. 1998, Alcock et al. 1999, Albrow et al. 1999, Becker et al. 1998, Sahu & Sahu 1998, Udalski et al. 1998). The observations are clearly in support of the idea that the SMC has a non-equilibrium structure extended in the line of sight (Caldwell & Coulson 1986, Mathewson, Ford & Visvanathan 1986, Welch et al. 1987, Westerlund 1997). While there is still some dispute about the interpretation of the two binary lens candidates LMC-9 (Bennett et al. 1996, Zhao 1998a) and 98-SMC-1 (Honma 1999, Kerins & Evans 1999), the consensus seems to be that self-lensing in the LMC and SMC is significant if not dominant. In general, models of the lens and source distribution to the LMC fall in two broad classes.

**Objects with motion decoupled from the Clouds.** These are dark objects or stars of origin independent of the MCs. They generally move with a velocity quite different from the MCs. Besides the Galactic dark halo, they include the thick disc, and maybe a segment of the warp of our Galaxy (Evans et al. 1998) or even a Sagittarius-like undigested substructure in the halo which by chance is in the foreground or background of the MCs (Zhao 1996). Recent observations, including RR Lyrae sample in the MACHO sample, are not in favor of chance alignment models. Stars in the warp would have small heliocentric velocities as they participate in the Galactic rotation just like the Sun. The hypothesized substructure should be a cold feature in the velocity range between $-300 \text{ km s}^{-1}$ to $300 \text{ km s}^{-1}$.

**Objects co-moving with the Clouds.** These are generally stars which are one way or another generated by dynamical processes in the formation and evolution of the MCs or their progenitor. A predicted orbital and tidal disruption history of the Ancient Magellanic Galaxy (AMG) is shown (the two right panels of Fig. 2) in a model for the progenitor galaxy (Zhao 1998b). The lower left is a plot of the end-result of an N-body simulation (kindly made available by Lance Gardiner) of the LMC-SMC-Milky Way interaction, which creates a rich variety of stellar and gaseous substructures shown here. Zhao (1996, 1998a,b) suggested lensing of several such substructures, loosely bound or completely unbound to the MCs. These include a completely unbound grand tidal arm of the MCs which extends to Ursa Minor and Draco, a localized common halo bridging the MCs, a tidally strongly deformed SMC, a polar ring structure or a tidal halo of the LMC (cf. Fig. 2). The LMC disc might also not be perfectly thin and flat. Similar to the Galactic disc, which has a strong warp at the edge of the disc due to perhaps tidal interaction with the LMC or the Sagittarius dwarf galaxy, the gas-rich LMC disc might sport
a thickened disc (Weinberg 1998) due to repeated harassment of the SMC and the Galaxy. All these models imply tidal interaction and could match observations, such as, the Magellanic Stream and its leading arm, proper motions of Ursa Minor and Draco, distributions of gas and stellar associations in the Magellanic Bridge, and a possible large line of sight extent of the SMC and a polar ring structure seen in the velocity distribution of LMC carbon stars (Kunkel et al. 1997). Weinberg’s model is also motivated by a diffuse structure seen in star count data of USNO2 which seems to end near the tidal radius of the LMC.

These extra stars surrounding the Clouds are still highly speculative with highly uncertain geometries. It is debatable whether their structure is better described as a thickened disc, or a warp, a flare, a polar ring, a tidal halo etc.. But the common feature is that they circulate around the Galaxy together with the Clouds. In this sense they can be called co-moving objects, with a proper motion and radial velocity typically within, say \(100\,\text{km}\,\text{s}^{-1}\), of MCs. For example, the Vertical Red Clump feature identified by Zaritsky et al. (1997, 1999) in their color-magnitude diagram of the LMC might be stars a few kpc in front of the LMC disc. If this interpretation

![Figure 1](image1.png)

**FIGURE 1.** Upper left: Magnitude and radius distribution of some 30 microlensing alerts (crosses) and published candidates (asterisks) towards the MCs. Lower left: Relative source-lens proper motion vs. the offset in radial velocity of lensed source from average LMC disc stars in the same field. Upper right: The radial velocity of stars in the general direction of the LMC as a function of the position angle. Lower right: Distribution of the same objects after removing the mean rotation of the LMC disc (the sinusoidal curve).
holds up against countering arguments, the VRC objects would belong to the co-moving class rather than an independent stream since they move with a velocity very similar to the LMC.

These models typically predict a lens-source separation $> 1$ kpc and events of diameter crossing time $> 30$ days for a $0.1M_\odot$ stellar lens, and require a total mass in tidal substructures above 10% of that of the LMC, or comparable to that of the SMC to produce significant lensing. The challenge is to keep a large amount of unbound material near the Clouds, unless they are born recently (say due to a recent SMC-LMC encounter) or they remain loosely bound. For example, part of the common halo or bridge in the simulation shown in Fig. 2 is loosely bound to the MCs. It contains about $10^9 M_\odot$ in a mix of gas and stars with a velocity dispersion of about 60 km s$^{-1}$ (Gardiner et al. 1994, 1996).

**Smoking Guns for the two broad classes of models.** Star-star lensing leaves detectable traces in the kinematical and spatial distribution of the lensed

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**FIGURE 2.** Upper left: Aitoff projections of a few halo dwarf galaxies and globulars, the Magellanic Stream, the disrupted Ancient Sagittarius Galaxy (ASG, along $l \sim 0^\circ$) and a sketch of a warped disc of the Galaxy. The Ancient Magellanic Galaxy (AMG) is the suspected common progenitor of objects on the great circle $l \sim 270^\circ$. Lower left: Simulated tidal structures along the Magellanic Stream and in the vicinity of LMC/SMC. The Sun-Galactic center line is along $Y = Z = 0$. Upper right: Predicted evolution of the distance from the Galactic center of the LMC, SMC, Ursa Minor and Draco for the past 6.5 Gyrs under the assumption that they come from a common progenitor. Lower right: Predicted history of tidal shocks (measured in ambient density) on the MCs, including a very recent one on the SMC.
sources. This is illustrated schematically by the right two panels of Fig. 1. The narrow sinusoidal band of the PA vs. \( \dot{V}_r \) plot is indicative of the rotation of the kinematically cold (dispersion less than 20 km s\(^{-1}\)) young thin disc component; an older, thicker disc would also rotate but with a larger dispersion. Overplotted are the predicted radial velocities of extra stars coming from either a decoupled component (triangles), which is clearly offset from the LMC, or a substructure comoving with the LMC (asterisks), which would generally show as a thicker band with either little dependence on the PA, or dependence different from the rotating disc (e.g., stars on the polar ring of Kunkel et al.). The co-moving material can be identified after subtracting the rotation (the lower right panel); they are markedly offset from the narrow distribution of the LMC thin disc stars. Here I propose a number of ways to resolve the substructures in the line of sight.

**I.** Self-lensing of stars comoving with the Clouds would induce a gradient of the event rate per survey star per year across the LMC disc since it is modulated by the structure of the LMC, whose width and density vary with the line of sight. The typical event time scale varies similarly. On the other hand if the lenses come from a smooth macho halo or any extended smooth structure decoupled from the MCs, it should be nearly the same for all lines of sight to the LMC disc. A tricky point here is that the dark halo could have fine structures, maybe a Sgr-like stream made of dark machos, which could induce a gradient as well.

**II.** Self-lensing prefers sources at the backside or behind the LMC disc. This is because lensing is most efficient if the source is located a few kpc behind a dense screen of stars, here the LMC disc. As a result, one should find a slight bias of lensed sources towards fainter magnitude than average stars in the survey, which are mostly LMC disc stars. Together with the spatial bias in (i) self-lensing should induce a bias in the magnitude vs. radius relation (maybe in the direction of the arrow in upper left panel of Fig. 1). No such bias is expected for macho models. Again there could be ambiguity if the stars at the backside of the LMC disc are systematically younger or older, hence intrinsically brighter or fainter.

**III.** Furthermore, these lensed sources behind the LMC disc are kinematically different from average stars in the LMC. This is perhaps the strongest signal of self-lensing since radial velocities can be measured so accurately that we can look for a small offset. There are two complementing effects here. First a radial velocity survey should pick up a small fraction of outliers of the rotation curve of the LMC disc (cf. right panels of Fig. 1), which may belong to some puffed-up distribution surrounding the LMC disc. Second the outliers at the backside of the LMC are more likely picked as lensed sources, with a velocity set apart from the rotation speed of the LMC disc *in the same field* by typically more than 20 km s\(^{-1}\) (cf. the lower left panel of Fig. 1). In contrast, if all events come from LMC disc stars being lensed by foreground Milky Way machos or disc stars, then the lensed sources would follow the motions of average stars in the cold, rotating disc.

**IV.** A continuation and expansion of the MACHO survey hopefully can yield a small sample of exotic events (e.g., when a source star passes the caustics of a binary lens) for which we can often tease out the relative lens-source parallax or proper
motion. Their distribution would be a direct probe of the dynamics and structure of the lens population. This effect can be integrated with the radial velocity bias to set part various lens populations (cf. lower left panel of Fig. 1). The potential has clearly been demonstrated by LMC-9 and 98-SMC-1, where the observed small relative proper motion also seems to favor lensing by stars co-moving with the LMC (asterisks and p.m. histogram) than lensing by foreground populations in the Milky Way (triangles and the broad Gaussian curve with a p.m. dispersion of 3mas/yr, typical for halo machos or Galactic thick disc stars). I expect a handful of such events in the next five years with an extrapolation of current surveys, while the Next Generation Microlensing Survey (NGMS, Stubbs 1998) holds the promise of a similar number of events each year. Again whether a sample of caustic crossing binary events is a fair sample depends on whether we expect the fraction of machos in close binaries to be the same as that of stars.

Detection or non-detection of these subtle effects would be the key to resolve the controversy of the Galactic dark matter. The radial velocity survey is by far the most promising approach since it is not limited to the rare high amplification (caustic) events, it is not essential to take spectra of the source star during lensing, and the effect is big and easy to detect. While the strength of each of the “smoking guns” are still subject to details of our assumptions of, e.g., the star formation history of the LMC and intrinsic properties of machos, a complementary studies of lensing-induced systematic bias in radial velocity, distance, proper motion and spatial distributions is likely to give a robust conclusion on the nature of Galactic dark matter. More detailed simulations of the velocity distributions of various structures will be reported elsewhere, together with discussions of optimal strategies of carrying out the proposed observations to lift current degeneracies in interpreting the microlensing data. Finally studies of these effects can all be integrated in the NGMS. Tests of these effects could be first done towards the Galactic bulge where self-lensing of the Galactic bar surely plays an important role. New constraints will also come from microlensing surveys towards M31 (Crotts & Tomaney 1996, Ansari et al. 1997). A more distant but exciting prospect is to complement ground-based microlensing light curves with astrometric follow-up observations with the SIM satellite (2005-2010). Furthermore, GAIA (under study for launching 2009-2014) could in principle detect microlensing on the basis of astrometric shift alone without relying on the alerting system from the ground. The relative proper motion and parallax of the lens and the source will be the definitive test of the lens location and kinematics.

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