Constraining the Locations of Microlenses Towards the LMC

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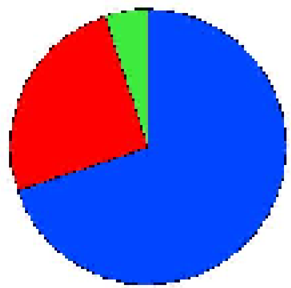
Outline

- Introduction
- Microlensing Searches for Halo Dark Matter
  - Microlensing geometry, basic concepts, observables
  - Results of Surveys
- The Location of the Microlenses and Microlensing Models
- Information from the Microlensing Source Star CMD $\longrightarrow$ Constraining location of microlensing source stars
  - Constructing model CMDs
  - KS test results, interpretation and analysis
  - STARFISH – synthetic CMDs
- Summary and Conclusions
- Future Plans $\longrightarrow$ Dark Energy Observables

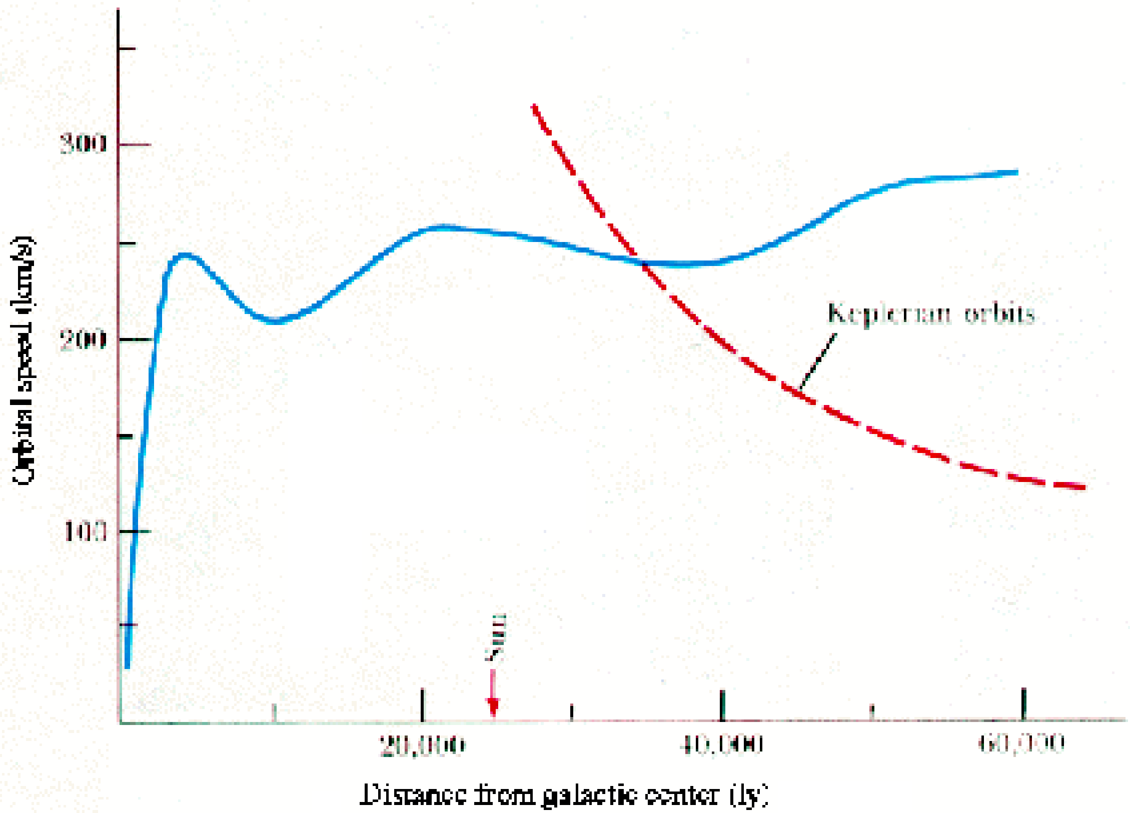
Introduction: Known Composition of the Universe



According to CMB, Supernova, Galaxy Cluster, and Big Bang Nucleosynthesis Studies, Universe Consists of:

- Green: $\sim 5\%$ Baryonic matter (atoms, molecules, dust, stars, planets, both visible and invisible)
- Red: $\sim 25\%$ Non-baryonic matter (invisible “dark matter”)
- Blue: $\sim 70\%$ Dark Enegy (Negative pressure causing cosmic acceleration)

Introduction – Evidence for Dark Matter: Rotation Curve of Milky Way



(Schombert, 2002)

Introduction: Evidence for Dark Matter

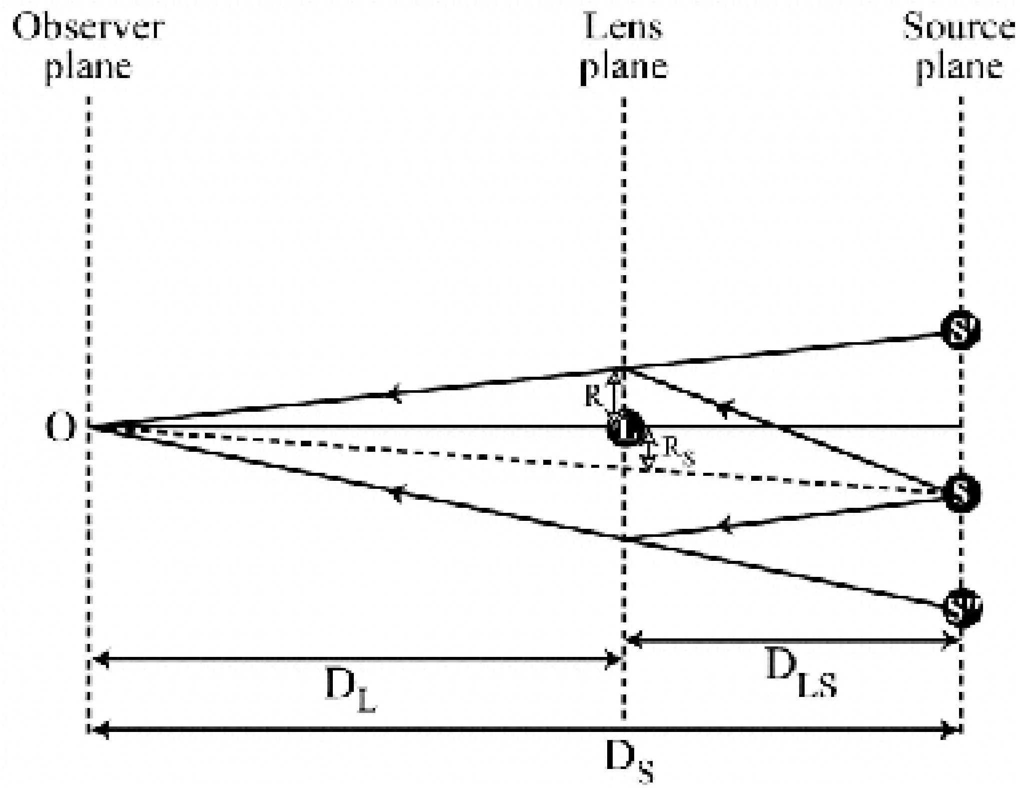
- (Flat) Galaxy rotation curves

Other evidence of dark matter includes:

- Big Bang Nucleosynthesis $\longrightarrow$ Baryonic matter
- X-ray measurements of galaxies $\longrightarrow$ Hot gas in galaxy clusters
- Velocity dispersions of galaxies within clusters
- Acoustic peaks in CMB power spectrum
- Gravitational Lensing

Microlensing Searches for Halo Dark Matter – Microlensing Geometry

(Sahu & Gilliland, 2003)



$$R_E^2 = \frac{4G}{c^2} M_L \frac{D_{LS} D_L}{D_S} \qquad \theta_E = \frac{R_E}{D_L}$$

The 3 observables (parameters) of microlensing events are:

- The maximum magni£cation, A_{max}
- The Einstein diameter crossing time or event duration, $\hat{t} = \frac{2\theta_E}{v_t}$
- Time of maximum magni£cation, t_{max}

Microlensing Searches for Halo Dark Matter – Microlensing Observables

$\theta_E = 0.902 \text{ mas}(\frac{\mathrm{M_L}}{\mathrm{M_\odot}})^{1/2}(\frac{10\mathrm{kpc}}{\mathrm{D_L}})^{1/2}(1-\frac{\mathrm{D_L}}{\mathrm{D_s}})^{1/2}$

Paczynski (1996)

For a lens of $\sim M_\odot$ at a distance of a few kiloparsecs

$\theta_E \sim 1$ mas

$\longrightarrow$ cannot resolve the two images and we see only the combined amplification

$A = \frac{u^2+2}{u(u^2+4)^{1/2}} \quad u(t) = \frac{R_s(t)}{R_E}$

The event duration is defined as

$\hat{t} = \frac{2\theta_E}{v_t} = 0.214 \text{ yr}(\frac{\mathrm{M_L}}{\mathrm{M_\odot}})^{1/2}(\frac{\mathrm{D_L}}{10 \text{ kpc}})^{1/2}(1-\frac{\mathrm{D_L}}{\mathrm{D_s}})^{1/2}(\frac{200\mathrm{km/s}}{\mathrm{v_t}})$

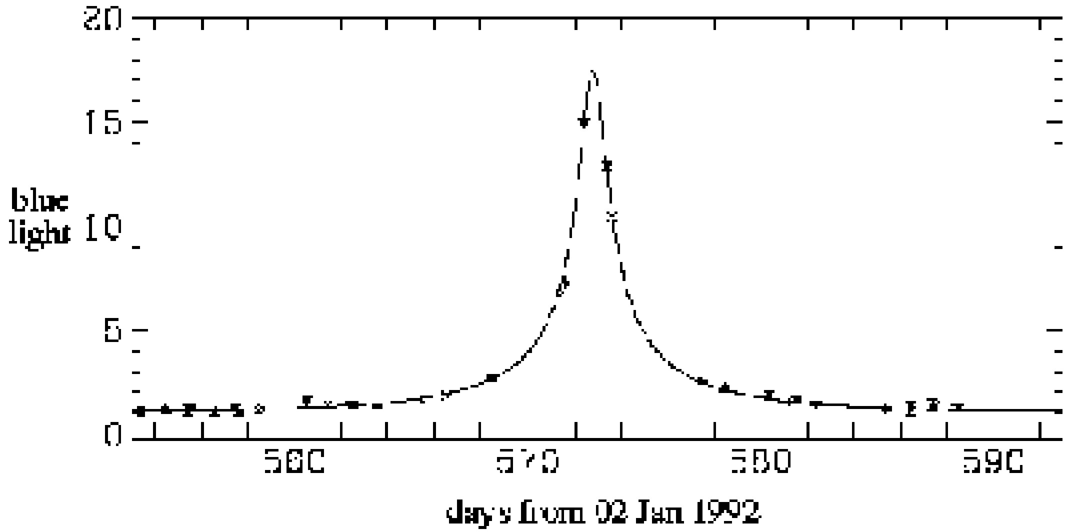
and is degenerate in all 3 fundamental parameters, the mass, distance

and velocity of the lens.

Microlensing Observables – Example of a microlensing event light curve

Light curve plot of magni£cation (ampli£cation) of microlensed source star vs. time.

Ampli£cation only depends on impact parameter.



(Alcock, *et al.* 1995, ApJ, 445, 133))

Microlensing Optical Depth

The microlensing optical depth, τ is the probability that a source star is being lensed at a given instant

$$\tau = \int_0^{D_s} \frac{4\pi G\rho}{c^2} \frac{D_L D_{LS}}{D_s} dD_L = \frac{\pi}{4E} \sum_i \frac{\hat{t}_i}{\epsilon(\hat{t}_i)}$$

A simple estimate of this for $\rho =$ constant yields

$$\tau = \frac{2\pi}{3} \frac{G\rho D_s^2}{c^2}$$

From the virial theorem $G\rho D_s^2 \sim v^2$ which gives

$$\tau \sim \frac{v^2}{c^2} \sim \frac{(220\ km/s)^2}{c^2} \sim 5 \times 10^{-7}$$

More detailed calculations (Griest, 1991, ApJ, 366, 412)) give

$$\tau = 5.1 \times 10^{-7}$$

The MACHO Project

Charles Alcock *et al.*

- MACHO project is one of number of microlensing searches for MAssive Compact Halo Objects (e.g., white dwarfs, neutron stars, black holes, brown dwarfs) in halo of the Milky Way (MW) on line of sight towards Large Magellanic Cloud (LMC).
- LMC was chosen as source background because:
  - Nearby galaxy provides background of bright source stars.
  - Away from plane of galaxy $\longrightarrow$ Reduces amount of foreground confusion.
  - On line of sight through the MW halo $\longrightarrow$ better enables search for MACHOs in MW Halo.

Results of Surveys – Microlensing search results towards LMC

MACHO Project results:

- Observed 11.9 million stars in LMC
- Found 13 to 17 events towards LMC in 5.7 years of observations
- MACHO halo fraction of $\sim 20\%$ for typical halo model
- Most likely mass of lenses estimated to be in range $0.15 - 0.9 M_{\odot}$
- Derived optical depth $\tau = 1.2 \pm 0.35 \times 10^{-7}$

Results of Surveys – Microlensing search results towards LMC

Unpublished EROS2 results

- Possibly $\sim 12 - 20\%$ of MW halo consists of MACHOs
- Mass of MACHOs are estimated to be in range 2.0×10^{-4} - $1 M_{\odot}$ range
- May be compatible with MACHO microlensing results

Results of Surveys – Microlensing searches towards Andromeda galaxy

Results from POINT-AGAPE, SLOT AGAPE, MEGA, Columbia-VATT collaborations:

- MACHO halo mass fraction of Andromeda is at least 20-25$\%$
- Average MACHO mass lying in the 0.5 - $1 M_\odot$ range
- Similar to MACHO collaboration's estimates for MW halo

Self-Lensing Optical Depth

Analytic estimate of optical depth for disk-disk lensing for self-gravitating thin disk yields

$\tau = \frac{2<v^2>}{c^2} \frac{1}{\cos i^2}$ (Gould, 1995)

For observed stellar velocity dispersion of $< v >\sim 20$ km/s and an LMC inclination angle of $i \sim 30$ degrees this yields

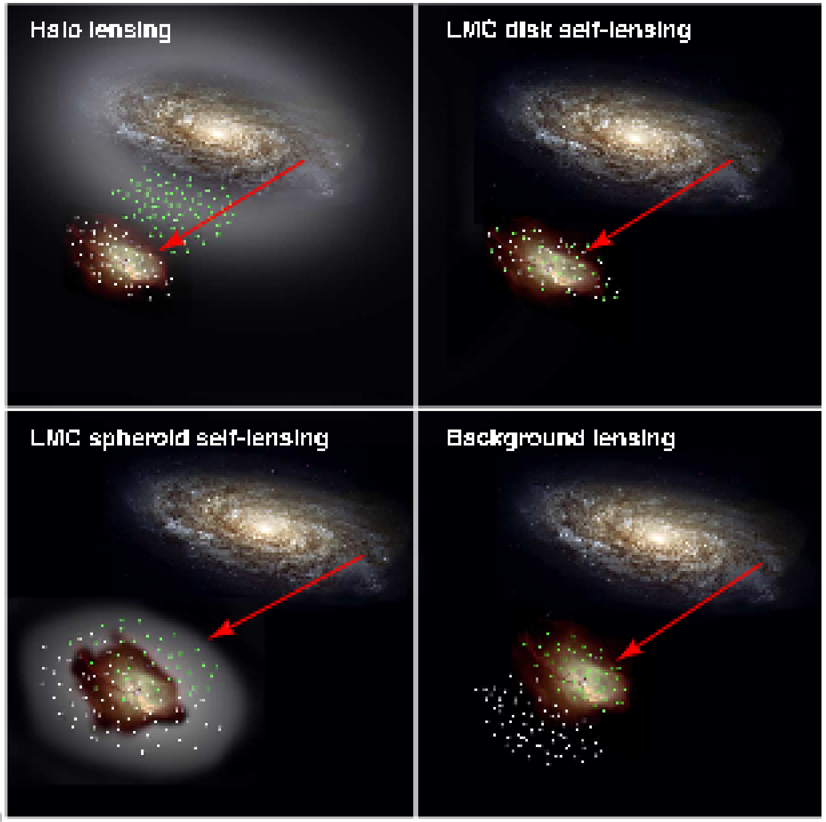
$\tau \sim 1 \times 10^{-8}$

Standard models of MW $\&$ LMC consistent with current observations yield LMC self-lensing optical depth of

$\tau \sim 2.4 \times 10^{-8}$

(Gyuk, Dalal $\&$ Griest (2000))

The Location of the Microlenses – LMC Microlensing Models



Green dots → lensing objects

White dots → source stars

Upper right: MW

Lower left: LMC

Nelson *et al.* ,2003 (Draft paper).

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- Future Plans ⟶ Dark Energy Observables

Constraining the Location of the Microlenses – Our Results and Ongoing work

- We attempt to constrain the locations of the microlensing source stars by continuing and expanding upon the work of Alcock, C. et al. 2001, ApJ, 114, 1933
- Alcock et al. 2001 used 8 microlensing source stars in their analysis; we use 13
- We also use model CMDs generated by the STARFISH code

Procedure for creating and comparing model LMC CMDs

- Start with HST CMD of average LMC population constructed by combining CMDs of 13 WFPC2 £elds centered on past MACHO micro-lensing events in outer LMC bar.
- Considered following four situations:
  1. sources in LMC $\longrightarrow$ lenses in MW (MW Halo-lensing)
  2. sources in LMC $\longrightarrow$ lenses in LMC (LMC disk self-lensing)
  3. sources in LMC disk or halo/shrowd $\longrightarrow$ lenses in LMC disk or halo/shrowd (LMC spheroid self-lensing)
  4. sources behind LMC $\longrightarrow$ lenses in LMC (Background lensing) (Zhao, Graff, & Guhathakurta, 2000)
- Assume source stars can be drawn from (1) bar & disk of LMC, (2) halo/shrowd of LMC, (3) background population behind LMC

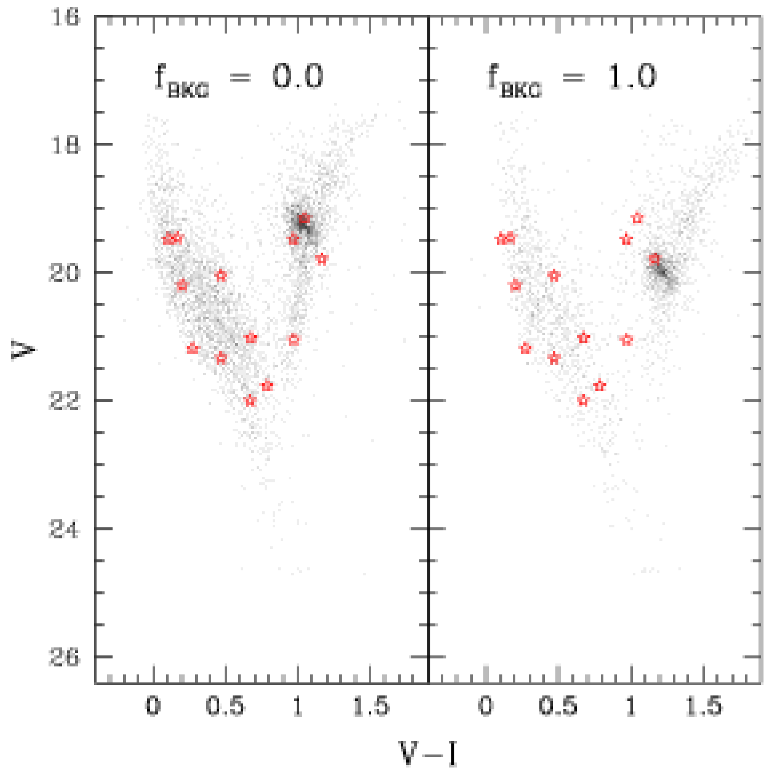
Constraining the Location of Microlenses – Procedure (continued)

- Assume background population does not differ intrinsically from population in LMC.
- Convolve MACHO micro-lensing detection ef£ciency with HST WFPC2 composite CMD to reproduce unblended population observed by MACHO experiment.
- Background population of source stars reddened by <E(V-I)> = 0.18 (Harris, Zaritsky, & Thompson, 1997)

Constraining Location of Microlenses – Procedure (continued)

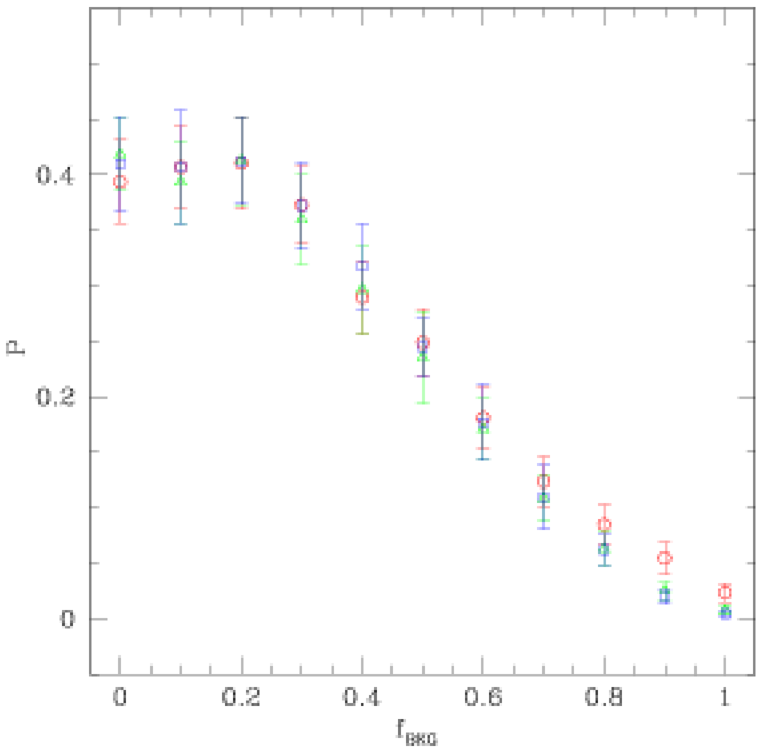
- Considered and tested 3 different displacement distances for background stars:
  - $\Delta\ \mu = 0.0$ (0.0 kpc) $\longrightarrow \Delta V = 0.43$
  - $\Delta\ \mu = 0.3$ ($\sim$7.5 kpc) $\longrightarrow \Delta V = 0.73$
  - $\Delta\ \mu = 0.45$ ($\sim$11.5 kpc) $\longrightarrow \Delta V = 0.88$
- Ran 2-D KS tests to determine model source star population most consistent with observed composite HST CMD

CMD of microlensing source stars vs. CMD of average LMC pop.



Continuing and expanding upon work of Alcock, *et al.* , 2001, ApJ, 552, 582. MACHO microlensing source stars (large, red stars) over-plotted on model populations representing all source stars in the LMC (left panel) and all source stars behind the LMC ($\Delta\ \mu = 0.3 \longrightarrow \Delta V = 0.73$) (right panel).

Constraining Location of Microlenses – 2-D KS Test Results



Continuing and expanding upon work of Alcock, *et al.* 2001, ApJ, 552, 582. 2-D KS test probability that observed distribution of microlensing source stars was drawn from source star population in which fraction f_{BKG} of source stars are located behind LMC. Background stars shifted by $E(V-I) = 0.18$; $\Delta\mu = 0.0, 0.3, 0.45$.

Interpretation and analysis of KS test results

- 2-D KS test probability P highest for $f_{BKG} \sim 0.0 - 0.2$ with little dependence on value of $\Delta\mu$
- Rule out model in which source stars all belong to background population at con£dence level of 99%
- Can rule out spheroid self-lensing models ($f_{BKG} \sim 0.65$) at con£dence level of $80 - 90\%$
- KS test results disfavor LMC disk-disk lensing (self-lensing)

Interpretation and analysis (continued)

Conclusion: KS test results & external constraints suggest that lens population comes from MW halo with smaller self-lensing contribution from disk & bar of LMC.

Constraining Location of Microlenses – Problems with analysis

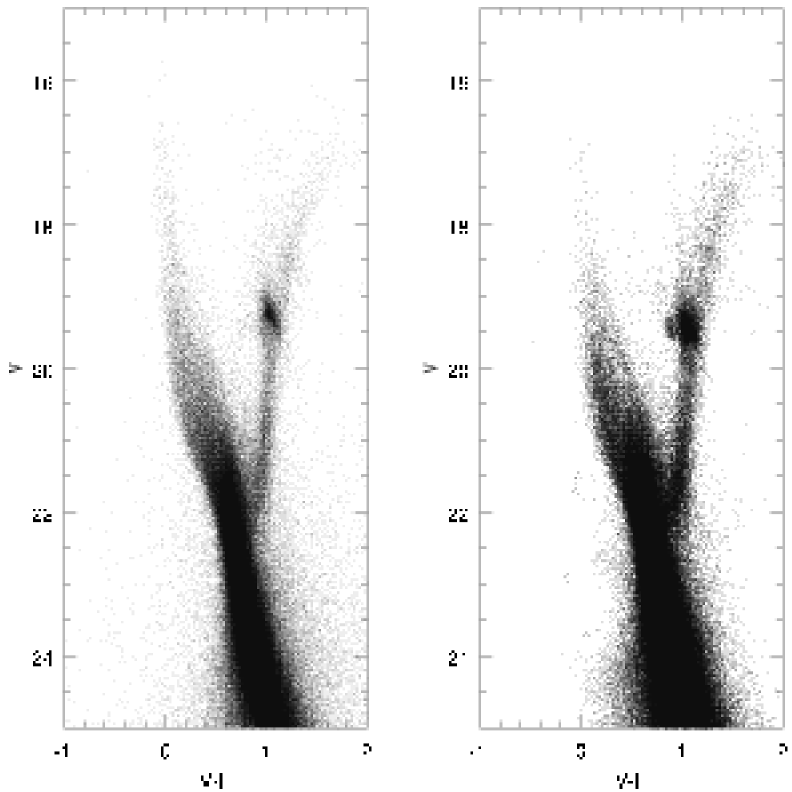
Problems:

- More microlensing events necessary to accurately determine f_{BKG} and eliminate other models.
- Observed CMD and model source star populations already includes background fraction, all other populations, and observed reddening.

Constraining Location of Microlenses: Ongoing work – Model CMDs

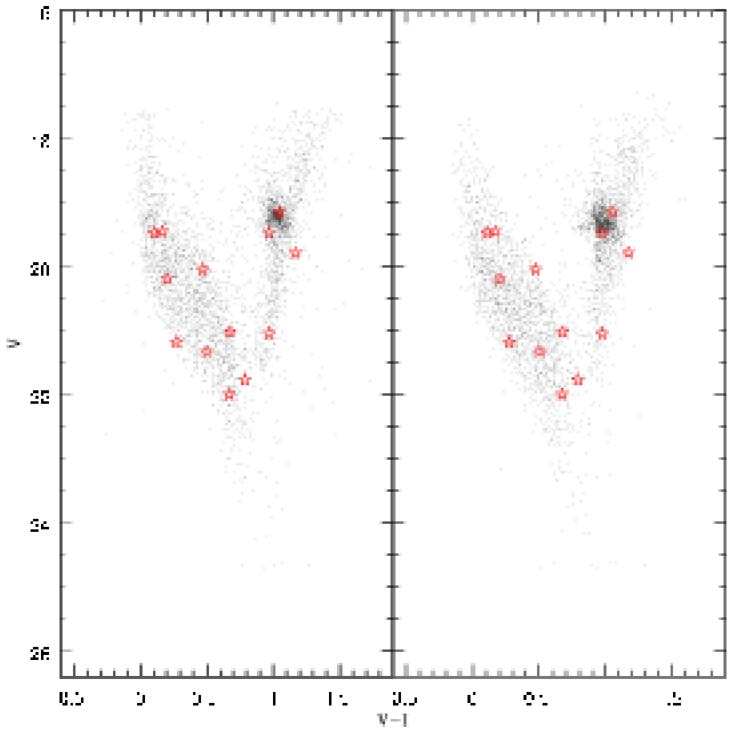
- Deriving underlying un-reddened stellar CMD using STARFISH synthetic CMD code package (Harris & Zaritsky, 2001) (`http://marvin.as.arizona.edu/~jharris/SFH/`)
- Constructing reddening models involving uniform reddening and Poisson distribution of cloudlets for populations supplying microlensing source stars.
- Convolve model CMD with microlensing detection ef£ciency.
- Compare reddened model CMD to observed source star CMD and 13 microlensing source stars using 2-D KS test.

Ongoing Work – Observed LMC CMD vs. STARFISH model CMD



Observed composite HST CMD of 13 LMC £elds surrounding each microlensing event. Right Panel: Example of composite best-£t STARFISH-generated model CMD of 13 LMC £elds.

Ongoing Work – Observed LMC CMD vs. STARFISH model CMD



MACHO microlensing source stars (large, red stars) overplotted on observed ef£ciency convolved CMD (left panel). MACHO microlensing source stars overplotted on ef£ciency convolved best-£t model CMD generated by STARFISH code, and reddened with Poisson-cloudlet model (represents $f_{BKG} = 0.0$ case).

Ongoing Work – Possible problems with STARFISH-generated model CMDs.

Luminosity function along MS may be getting too much weight in model CMDs.

Also, isochrones may not model the red giant stars as well as younger stars in the CMD (Olsen, 1999, ApJ, 117, 224) because stellar evolution theory can not yet model later stages of stellar evolution (e.g., RGB) as well as younger stars (e.g., main sequence)

$\longrightarrow$Fit between theory and observation is poorer for RGB than for MS and AGB.

$\longrightarrow$Uncertainties in calculations become large when trying to follow these later stages of stellar evolution.

$\longrightarrow$Synthetic RGBs and RCs appear wider or more smeared out than in real data.

Summary and Conclusions

- CMB & B.B.N. studies indicate that most of mass of universe exists in form of invisible “dark matter”.
- Some of this dark matter in baryonic form and may be located in dark halos of galaxies.
- Several experiments, including MACHO, have carried out microlensing searches of baryonic halo dark matter in form of MACHOs
- Estimates from MACHO and other collaborations indicate that up to $\sim 20\%$ of MW halo may consist of MACHOs in $0.15 - 1 M_{\odot}$ range.
- Attempted to constrain location of source stars, and therefore lenses, by constructing model CMDs.

Summary and Conclusions (cont.)

- KS test results & external constraints suggest that lens population comes from MW halo w/smaller self-lensing contribution from disk & bar of LMC.
- Ongoing work invovles constructing synthetic CMDs for deriving underlying un-reddened CMDs and then constructing various reddening models to recreate any populations interested in testing.

Future Plans: Dark Energy Observables

Research in transition.

- Exploring importance of different dark energy observables by investigating their utility in discriminating among range of theoretical models.
- Comparing different methods of exploring dark energy and assessing among number of different methods of observation.
- Learning how to use computational tools developed by Prof. Albrecht.
- Expanding these tools to include new theoretical ideas.
- Using these tools to explore space of theoretical dark energy models and determining how well a range of different observables can discriminate among them.