Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Microlensing

Principal Investigator: Andrew P. Gould

Team Members:
David P. Bennett (Univ of Notre Dame), Andrew Boden (JPL), Darren L. Depoy (Ohio State Univ), Scott B. Gaudi (Ohio State Univ), Kim Griest (UC San Diego), Cheongho Han (Chungbuk Nat'l Univ), Bohdan Paczynski (Princeton Univ), I. Neill Reid (Univ of Penn)

Introduction: A Galactic census

The primary goal of our project is to make a complete census of the stellar population of the Galaxy. We are broadening the term "stellar" here to include both ordinary stars and dark stars. Ordinary stars, burning their nuclear fuel and shining, can perhaps best be studied with traditional astronomical techniques, but dark stars, by which we include old brown dwarfs, black holes, old white dwarfs, neutron stars, and perhaps exotic objects such as mirror matter stars or primordial black holes, can only be studied by their gravitational effects. Traditionally, these objects have been probed in binaries, and thus selected in a way that may or may not be representative of their respective field populations.

The only way to examine the field population of these stars is through microlensing, the deflection of light from a visible star in the background by an object (dark or not) in the foreground. When lensed, there are two images of the background star. Although these images cannot be resolved when the lens has a stellar mass, the lensing effect can be detected in two ways: photometrically, i.e. by measuring the magnification of the source by the lens, and astrometrically, i.e. by measuring the shift in the centroid of the two images.

Photometric microlensing experiments have detected hundreds of microlensing events over the past decade. Despite its successes, photometric microlensing has so far been somewhat frustrating because these events are difficult to interpret. Almost nothing is known about the masses of individual lenses and very little is known about the statistical properties of the lenses treated as a whole, such as their average mass. Although probably over 100 of the lenses are in fact dark objects, we can't determine which they are, let alone investigate finer details such as what their masses are, and where they are in the Galaxy.

With SIM, we will break the microlensing degeneracy, and allow detailed interpretation of individual microlensing events. We will thus develop a detailed census of the dark and luminous stellar population of the Galaxy.

Breaking the microlens degeneracy

The difficulty in interpretation is due to the microlensing degeneracy. Each microlensing event is determined by three parameters, the lens-source relative parallax and proper motion, and the mass of the lens. Unfortunately, in the vast majority of events today, we can only measure one physical parameter, the event time scale, which is related to these three. This microlensing degeneracy makes any individual event impossible to interpret, and also stymies most of the interpretation of a statistical sample of events.

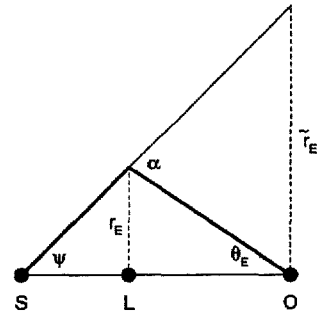

Figure 1: Illustration of the two key parameters that SIM will measure: the Einstein angle, θ_E which is the displacement of the image from the true position of the source, "S", as observed from the Earth, "O", and the projected Einstein radius, $\tilde{r}E$, which describes the characteristic distance an observer would have to move to see a significant change in the lensing event. If we can measure these observables, we can determine all physical features of the lens, "L". For the vast majority of microlensing events, neither of these parameters can be measured from the ground, but both can be measured with SIM.

First note from Fig. 1 that, using the small angle approximation, $D_l = \tilde{r}E/\alpha = r_E/\theta_e$. Hence,

$$\theta_E \tilde{r}E = \alpha r_E = \frac{4G}{c^2} M \tag{1}$$

Where we have made use of the Einstein light-deflection formula $\alpha = 4GM/r_E c^2$. That is, the mass is completely determined from the product of θ_E and $\tilde{r}E$.

How can one measure these two parameters? The Einstein angle, θ_E is roughly the difference between the position of the two images of the source when lensed and its true position. Thus, in principle it could be measured by simply comparing the positions of the images during the lensing event with the source postion after the event. Even SIM will not be able to resolve the two images of the source. However, one of the two images will be brighter than the other, and the centroid of light of the two blended images will be shifted slightly from the true position of the source towards the brighter image during the lensing event, typically by about 100 μas. With its 4 μas precision, SIM will be able to accurately measure this shift, and so θ_E.

To measure $\tilde{r}_E$, we can imagine a vast array of telescopes distributed around the solar system, each searching for photometric microlensing, the magnification of a source star by the lens. Only those telescopes within $\tilde{r}_E$ (typically a few AU) of the point perfectly aligned with the source and the lens will see any magnification. In practice, only two telescopes are needed, one on Earth, and one elsewhere in the solar system. From the difference in the event as seen by these two telescopes, one can reconstruct $\tilde{r}E$. Since SIM will be in a trailing solar orbit, moving away from the Earth at 0.1 AU/yr, SIM photometry (a byproduct of its astrometric observations) can be used to determine $\tilde{r}E$ in this manner.

Thus, using the unique capabilities of SIM, its μas astrometry and its solar orbit, we will be able to completely solve the event and measure the mass, location, and speed of the lens.

Using this method, we will learn what and where are the stellar components of the Galaxy, in the disk, the bulge, and the halo.

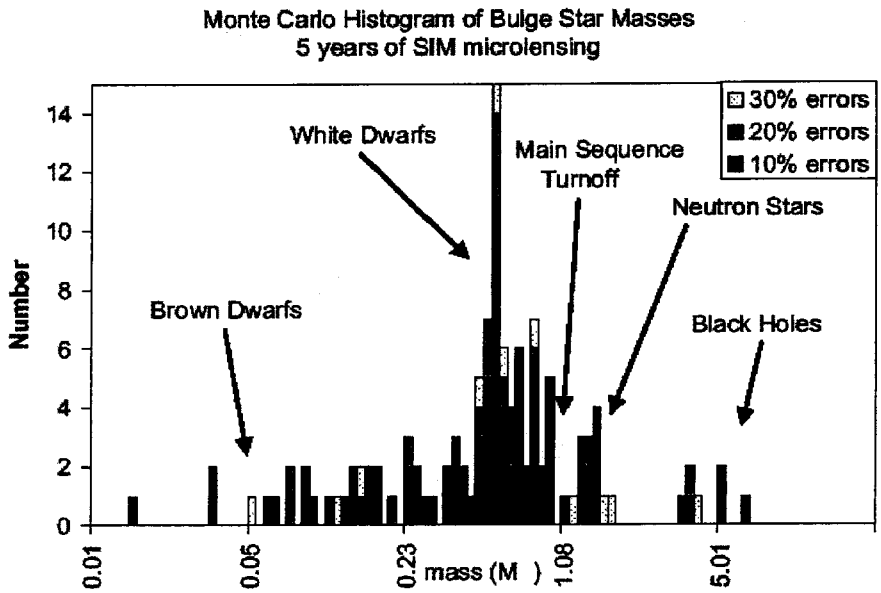

Figure 2: A Monte Carlo realization of how SIM will measure the combined mass function using astrometric microlensing.

The Galactic mass function

The present day mass function of luminous objects is reasonably well determined, but that of dark objects is totally unknown. A Monte Carlo realization of how SIM will measure the combined mass function using astrometric microlensing is shown in Fig. 2. Notice that it has several interesting features. There are distinct bumps for various different stellar remnant populations: white dwarfs, neutron stars, and black holes. The contributions of these dark objects to the mass of the Galaxy will be uncovered, as will some details of their individual mass functions.

The mass function is determined over two orders of magnitude in mass: we can study the initial mass function of stars well below the hydrogen burning limit, which will allow us to probe a possible brown dwarf cuttoff. Any kinks, breaks, or other features will be real, not due to any theoretical mass-luminosity-age relation. These features will give clues to star formation, and a comparison between the bulge mass function and the local mass function will help determine the effect of metallicity and environment on star formation.

Since the Galactic bulge is generally considered a proxy for old spiral bulges and ellipticals, a detailed understanding of its MF (including both dark and luminous stellar objects) will provide essential insight into these systems which contain the majority of the stellar mass in the universe. The bulge MF cannot be measured over this mass range by any other proposed technique, whether ground-based or space-based.

In addition to the mass of the lens, we will also be able to measure its distance and transverse velocity. Whereas in the past, using purely photometric microlensing, we were merely able to say that there was a lens somewhere along the line of sight, we will now be able to sort each lens by Galactic component as well as by mass, leading to further insights into the structure of the Galaxy.

Nature of the Dark Halo

The original motivation for the past decade of microlensing research was to determine whether the dark halo is composed of discrete lumps of mass, massive compact halo objects (MACHOs). Current results by the MACHO collaboration find a microlensing optical depth towards the LMC consistent with 20% of the mass of the halo being composed of MACHOs, an order of magnitude greater than could be caused by any known stellar population.

This result has defied simple explanation, leading to a number of proposed, but somewhat strained explanations. Either the lenses *are* in fact in the halo, in which case, they must be some exotic object (ordinary dark lenses such as white dwarfs and brown dwarfs have been ruled out), or the lenses must be in or near the LMC. Resolving this dilemma requires determining the location of the lens.

The location of the lens is bedevilled by the same degeneracies discussed above. Of the tens of lenses observed towards the Magellanic Clouds, only two lenses have been conclusively located, both in the SMC, and these two lenses are unique in several ways and may not be representative of the lensing population as a whole. Fortunately, SIM can determine the location of the lenses in a similar manner as the mass of the lens. From Fig. 1 and the exterior angle theorem:

$$\frac{\theta_E}{\tilde{r}E/\mathrm{AU}} = AU\left(\frac{\alpha}{\tilde{r}E} - \frac{\psi}{\tilde{r}E}\right) = \frac{\mathrm{AU}}{D_l} - \frac{\mathrm{AU}}{D_s} \equiv \pi_{\mathrm{rel}}. \tag{2}$$

where $\pi_{\mathrm{rel}} = \pi_l - \pi_s$ is the lens-source relative parallax. Lenses in the halo should have a large π_{rel}, lenses in the magellanic clouds will have a negligible π_{rel}. We will measure π_{rel} for five magellanic cloud lenses. If all five have negligible π_{rel} then we will know that the lensing is due to ordinary stars around the Magellanic Clouds. If some or all of the lenses have a measurable π_{rel}, then we will know that a substantial part of the mass of the Galaxy is made of some exotic objects.

Masses of nearby stars

In a distinct, but related experiment, astrometric microlensing of nearby stars provides an alternate route to measuring stellar masses with high accuracy. We have examined catalogs of proper motions stars to determine when nearby stars will pass in front of a more distant star, close enough to allow a measurable deflection of its light. By measuring this deflection with SIM, we will determine the mass of the nearby star to 1% accuracy.

Astrometric microlensing nicely complement traditional measurements of the masses of nearby stars. First, it works by a completely different physical principle than the standard methods. It will be especially useful in uncovering any systematic errors in the traditional mass measurements. Second, it works for single stars (and components of binaries with much wider separations than visuals), and can thus test whether or not binarity has any effect on the mass of stars. Third, the selection bias is toward high proper-motion (hence low-metallicity, [Fe/H] ~ -2) stars. At present, no low metallicity stars have accurate mass measurements.

Conclusion

With SIM, we will be able to measure the deflection of light by individual stars. We will thus be able to break the microlensing degeneracy and measure the mass, distance, and velocity of the

lens. SIM thus opens up a new method of surveying the Galaxy, determining what objects are where, how many, and of what mass, irrespective of whether those objects are bright stars in the bulge, white dwarfs in the disk, or dark matter candidates in the halo. Astrometric microlensing with SIM will measure the masses of nearby stars by a new technique that is competative with and complementary to the traditional method of observing binary stars.