Whipple: Exploring the Solar System Beyond Neptune Using a Survey for Occultations of Bright Stars

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1. Introduction and Science Drivers

The Whipple mission will reach deep into the outer Solar System, conducting a blind survey for occultations of bright stars by small, distant objects. This technique can detect objects even in the Oort Cloud. Observations of stellar occultations will reveal information about the numbers and sizes of objects in the outer Solar System, as well as crude estimates of distances. Detailed orbital information will not typically be available.

Our understanding of the Solar System is based on the tight connection between theory, modeling, and observation. There remains, however, an enormous gulf between theoretical models and observation. Theories show the Oort Cloud extends beyond 20,000 AU from the Sun (the tidal radius of the Solar System is >100,000 AU), while our observational horizon is modest, reaching just beyond the Kuiper Belt. It is time to advance the observational horizon of Solar System science to ∼10,000 AU or further!

1.1. Simulations of the Outer Solar System

Dones et al. (2004a) conducted a series of simulations of the processes that populate the outer Solar System. The authors made clear that they did not believe these simulations to be definitive[1], but their investigations illustrate the processes very clearly. Planetesimal formation occurred in the inner Solar System, where the densities in the proto-planetary disk were sufficiently high to allow growth. Scattering of smaller bodies by the giant planets led to the dramatic migrations of the giant planets. For the smaller bodies, many were lost from the Solar System on hyperbolic orbits, some were relocated to the present Kuiper Belt, and many intermediate objects ultimately populated the Oort Cloud.

The growth of the Oort Cloud included critical intermediate steps. These objects were first scattered into orbits with semi-major axes that placed them in the present day scattered disk, but with perihelia still inside the planetary zone. Subsequent gravitational encounters with Neptune increased the semi-major axes in a stochastic process, but the perihelia remained in the planetary zone. When the semi-major axis of an orbit grows to 3,000 AU and larger the mean tidal field of the Milky Way and occasional encounters with stars and molecular clouds lift the perihelion out of the planetary zone, and begin also to produce an isotropic distribution of orbits.

Some very general conclusions can be drawn from these simulations. One is that the structure of the Oort Cloud changes dramatically at ∼3,000 AU: orbits interior to this are generally at low ecliptic latitude, while orbits exterior to this are more nearly isotropic. Additionally, there are comparable numbers of bodies interior to and exterior to ∼10,000 AU. The exterior orbits are the source of new long-period comets (Duncan et al. 1987; Dones

[1]Dones et al. (2004a) also made clear the deep heritage of their work, encompassing a broad effort in this community.

et al. 2004a).

1.2. The Oort Cloud

The existence of a vast cloud of comets surrounding the Solar System and extending to nearly interstellar distances was first proposed by Oort to explain the energy distribution of the orbits of long-period comets (LPCs). About one-third of LPCs were found to have semi-major axes $> 10^4$ AU, yet still gravitationally bound to the Sun. Oort recognized that these comets must be coming from a vast reservoir. There must also exist an inner cloud that does not supply comets to the inner planetary region except in cases of extreme perturbations of the Oort Cloud (Hills 1981). As discussed above, the orbits of comets in the inner cloud have not been fully randomized by external perturbers and are more closely confined to the ecliptic plane.

Population estimates suggest that the outer cloud comprises $\sim 10^{12}$ comets with nuclei >2 km in diameter, with a roughly equal or larger number in the inner Oort Cloud. This leads to an estimate of > 7 $M_{\oplus}$ for the total mass of comets in the Oort Cloud (Dones et al. 2004b).

1.3 Sedna

The simulations described above do not produce any objects in orbits like Sedna. Sedna is in an orbit with the perihelion too large to be significantly affected by Neptune, and with an aphelion distance too small to be perturbed by Galactic tidal forces and giant molecular clouds. *Processes including only the known bodies in the Solar System do not place objects in orbits of this kind.* This has led to speculation that a very close encounter with another star in the birth cluster of the Sun scattered Sedna into its present orbit (Brasser et al. (2006) and references therein). This process would have populated the same region of phase space with smaller bodies, in proportion to their relative number, that originated in a similar region. The size spectrum of these bodies would tell us whether the critical encounter occurs before, or after, collisional grinding reduces the number of smaller bodies (as appears to have happened in the Kuiper Belt).

1.4 The Kuiper Belt

Much more is known about the Kuiper Belt than about the Oort Cloud following the spectacular observational and theoretical progress since 1992 (Jewitt & Luu 1993). Large-scale surveys covering a wide range of scales have discovered ∼1,000 Kuiper Belt Objects (KBOs) with diameters between ∼50 km and >1,000 km, in orbits that extend from ∼35 AU out to at least 150 AU. Most of the known KBOs have semi-major axes less than 50 AU, and it appears that this outer "edge" is real. The orbits have a broad range in eccentricity and inclination, extending higher than 30° out of the ecliptic plane.

The history of collisions among KBOs is revealed in the size spectrum of objects smaller than 100 km (Pan & Sari 2005; Kenyon & Bromley 2004). The direct surveys are incomplete for these bodies, which are typically too faint for most direct surveys (but see Bernstein et al. (2004); Fuentes et al. (2009); Fraser et al. (2008)).

2. The Occultation Technique: A New Approach

No object has been detected to date at Oort Cloud distances! This can be achieved using the occultation technique, which is simple in principle, but very challenging in application (Roques et al. 2009). An occultation is manifested by detecting the reduction in the flux from one of the stars for a brief interval. The rate of occultations is recorded over the time span of the observations. The measured rate is proportional to the number of objects, and the measured depths and durations of the occultations give rough size and distance information. The implementation of this idea is complicated by the short expected duration of an occultation event (typically less than a second), by the very low event rate, and by diffraction diluting the depths of the occultations (diffraction also sets a minimum occultation duration, given by the Fresnel length scale). Figure 1 shows occultations by spherical objects of a range in size, at three representative distances.

Several groups have conducted occultation surveys using ground-based telescopes. The most sensitive survey results published by the Taiwanese American Occultation Survey, reported no detections in over 150,000 star-hours of observations (Zhang et al. 2008). These surveys show both the power and the limitations of ground-based work. The principle difficulty is poor photometric stability due to atmospheric scintillation at the high cadences necessary to detect occultations. The current surveys plan to continue and extend their work, but their reach will be confined to the Kuiper Belt and, to some degree the scattered disk. The Sedna region is partially accessible (∼100 AU). The Oort Cloud is beyond the reach of ground-based surveys.

3. Whipple: A Discovery Class Mission to Survey the Outer Solar System

Whipple is a concept for a high speed photometric survey conducted in space to survey for occultations by small bodies from the Kuiper Belt through the Sedna region and into the Oort Cloud. The mission would comprise a small telescope with a wide field of view and a very large camera. The imaging devices would be newly developed CMOS detectors that allow very rapid read-out and low read noise. The parameters of the spacecraft and science payload are described in Table 1. Images would be processed on board; possible occultation signatures would trigger a download of all the imaging data spanning a candidate event.

This mission would produce continuous photometric histories of bright ($R < 14$) stars at high signal to noise and cadence. Carefully selected standard star fields would be distributed across the sky to allow a comprehensive survey of ecliptic and high latitude populations. Standard fields will be selected that contain ∼40,000 target stars, sufficient to guarantee a useful detection rate. Analysis of the diffraction fringes in events will allow crude estimates of distances to the occulting objects. The event rate will allow population densities to be estimated, while the depths and durations of events will allow sizes to be estimated. A small fraction of the events, those due to KBOs with diameters $>$ 30 km (corresponding to V=27.4 mag, assuming albedo of 0.04 and at 42AU), will be followed up using large telescopes on the ground; albedos will be estimated for objects that are recovered by this process.

Whipple will address the following key science questions:

- How many small bodies ($\sim$5 km) inhabit the inner Oort Cloud (out to $\sim$20,000 AU)?
- Does the inclination distribution of orbits flare from flattened to isotropic beyond $\sim$3,000 AU?
- What are the number, size distribution, and spatial distribution of small objects in the Sedna region?
- What is the size spectrum of small objects (down to $\sim$300 m) in the Kuiper Belt?
- What is the mean albedo of $\sim$30 km KBOs?

Figure 2 summarizes Whipple's power on a plot of object size versus semi-major axis. Known objects inhabit the "near and large" upper left corner. The limit of direct imaging is generously shown at magnitude R=30. The bold squares show examples of objects that Whipple will be able to detect. *Whipple will reach from the Kuiper Belt out to the Oort Cloud, providing direct empirical data for the first time in history.*

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Table 1: Whipple spacecraft and science payload parameters.

The Telescope		The Imagers	
Primary diameter:	1000 mm	Imager array:	1k x 1k CMOS Minimal (Sarnoff)
Full Field Angle:	7 degrees	Pixel size:	16 μm
Focal length:	950 mm	Thickness:	25 μm thinned, backside illuminated
Aperture diameter:	766.7 mm	QE:	>80 %
F ratio:	1.24	Readnoise:	5 electrons rms (total system noise)
Focal plane diameter:	117 mm	Readout rate:	40 Hz (full frame or window)
		Output channels:	4 per device

Orbit, telecom
100,000km circular
28.5 degrees inclination
Average download volume 4,680 mbits/day

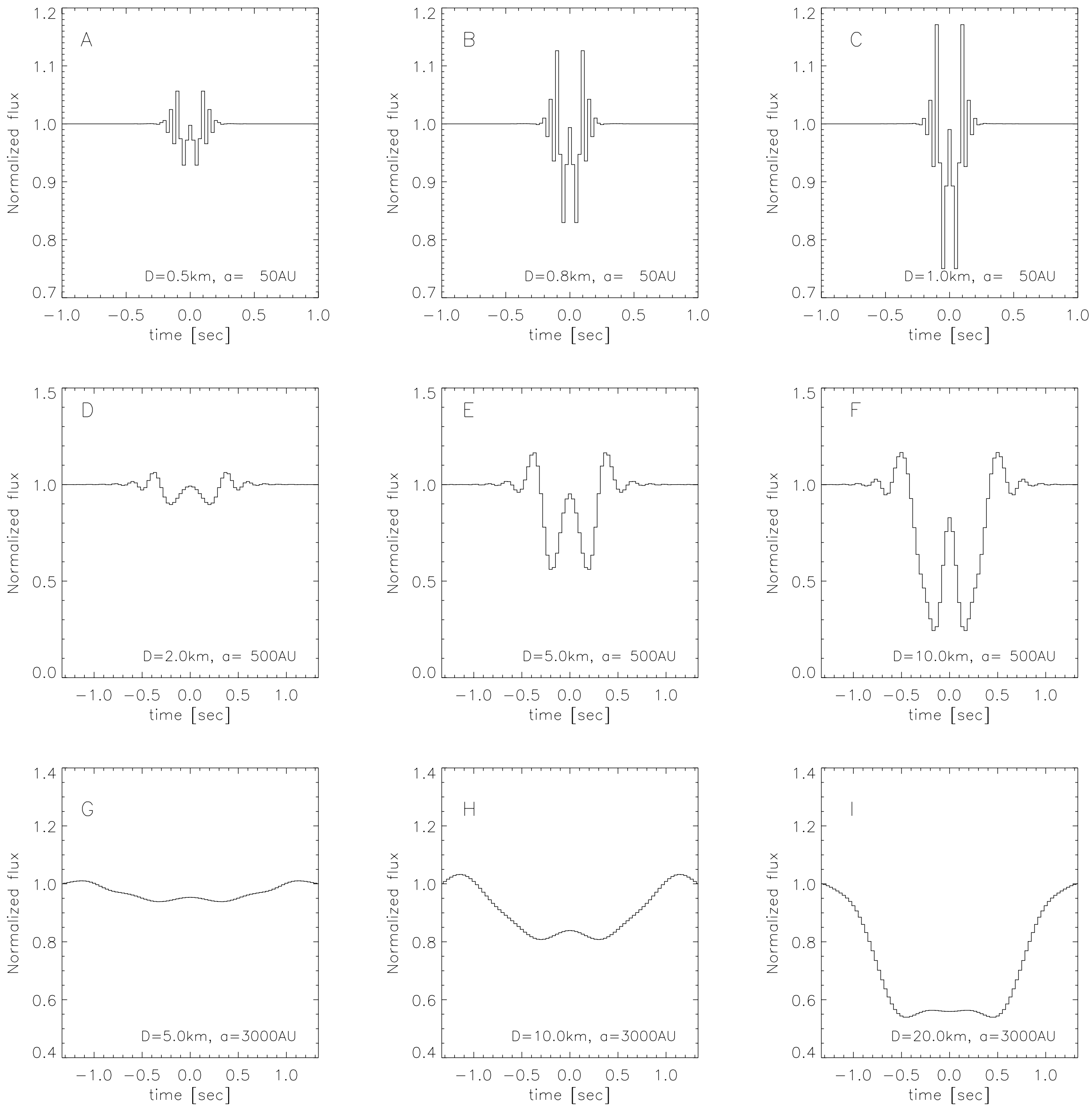

Fig. 1.— Occultation light-curves (relative brightness vs. time) of stellar occultations by objects of different sizes and various distances. Each light-curve was created using a sampling rate of 40Hz and stellar angular size of 0.015mas (equivalent to V=12 G0V) and zero impact parameter (impact parameter is straightforward to model). Top row: objects with diameter 0.5, 0.8, 1.0 km at 50AU. Middle row: objects with diameter 2, 5, 10 km at 500 AU. Bottom row: objects with diameter 5, 10, 20 km at 3000 AU. Given its anticipate detection limit, Whipple will be able to detect all of these signals.

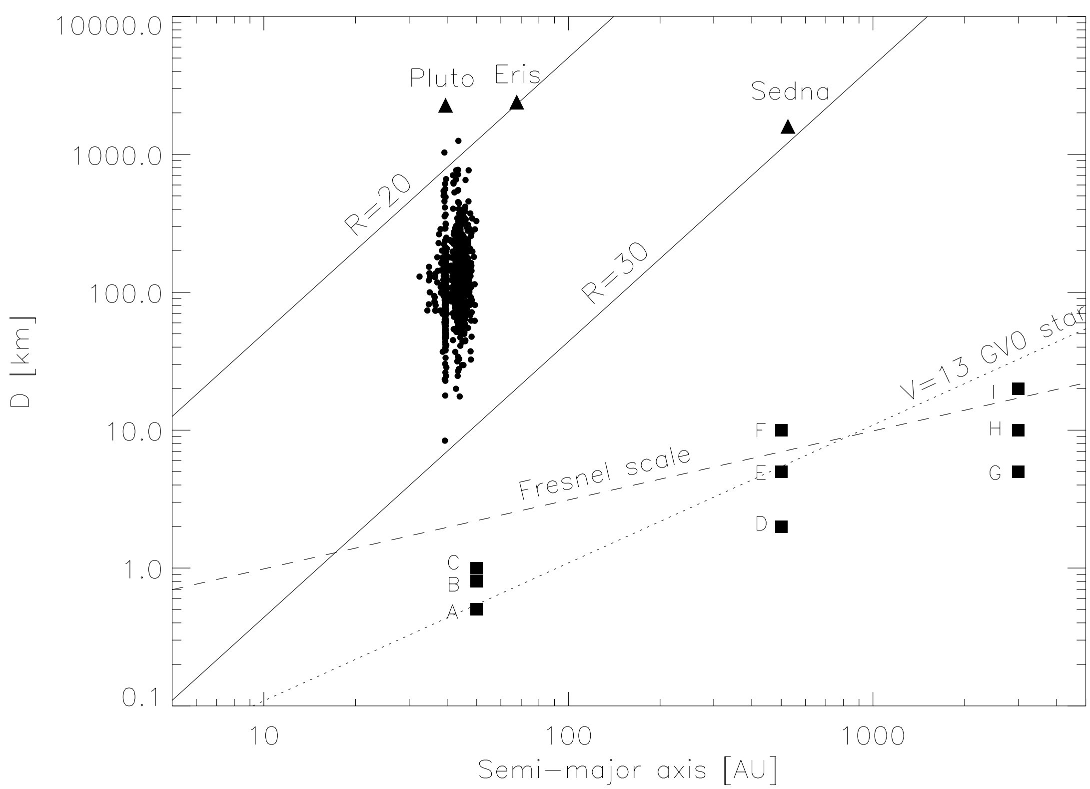

Fig. 2.— Diameter versus semi-major axis. The black dots show the known KBOs. The triangles indicate several of the larger, well-known outer Solar System objects at their semi-major axes, rahter than from their current distances. The solid lines indicate contours of constant brightness in reflected sunlight, assuming an albedo value of 0.04 . The long dashed line shows the Fresnel scale as a function of distance assuming $\lambda = 650$nm. Occultations by objects below this line are diffraction dominated. The dotted line is the angular size of a V=13 G0V star as a function of distance. The square points indicate the parameters (distance, diameter) used to generate the light-curves in Figure 1.