ORIGIN OF OUTER SOLAR SYSTEM

GRANT NAG5-13276

FINAL REPORT

For the period 01 June 2003 through 30 November 2004

Principal Investigator

Dr. Matthew J. Holman

May 2005

Prepared for

National Aeronautics and Space Administration

Greenbelt, Maryland

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory is a member of Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is
Dr. David Lindstrom, NASA Headquarters, Code S
Washington, D.C. 20546-0001

Our ongoing research program combines extensive deep and wide-field observations using a variety of observational platforms with numerical studies of the dynamics of small bodies in the outer solar system in order to advance the main scientific goals of the community studying the Kuiper belt and the outer solar system. These include: (**1**) determining the relative populations of the known classes of KBOs as well as other possible classes; (**2**) determining the size distributions or luminosity function of the individual populations or the Kuiper belt as a whole; (**3**) determining the inclinations distributions of these populations; (**4**) establishing the radial extent of the Kuiper belt; (**5**) measuring and relating the physical properties of different types of KBOs to those of other solar system bodies; and, (**6**) completing our systematic inventory of the satellites of the outer planets.

I. Work Completed

During the last full funding cycle, and its no cost extensions, we have conducted a large number of projects, both observational and theoretical, toward these goals. Below we describe these projects and their results.

A. Wide-field Searches for Kuiper Belt Objects

Since July 1999, we have conducted a large number of searches using the Canada-France-Hawaii 3.6m telescope with the CFH12K mosaic camera, the 4m Mayhall KPNO and 4m CTIO telescopes with their 8k mosaic cameras. All together we have covered ~ 25 square degrees of sky to $m_R \sim 24$ and have discovered and reported ~ 50 new objects. These surveys have been used to help constrain the cumulative luminosity function. The combination of ecliptic longitudinal coverage and range of ecliptic latitudes that we have searched will allow us to constrain the relative populations of different classes of KBOs as well as to constrain their inclination distributions.

B. Pencil-beam Searches for Kuiper Belt Objects

In addition to our wide-field searches, we have conducted three "pencil-beam" searches in the past year. In a pencil-beam search we take repeated integrations of the same field throughout a night. After preprocessing the resulting images we shift and recombine them along a range of rates and directions consistent with the motion of KBOs. Stationary objects then smear out, while objects moving at near the shift rate appear as point sources. We have not only demonstrated and refined this technique, but it allows us to reach two full magnitudes below the single exposure detection limit in a night of integration. The final scientific result from a pencil-beam search is measure of the sky surface density at a particular ecliptic longitude and latitude. As with the wide-field searches, our pencil-beam surveys have been conducted at a range of ecliptic longitudes and latitudes.

Gladman B, Kavelaars J, Petit J-M, Morbidelli A, Holman M, Loredo T (2001) The Structure of the Kuiper Belt: Size Distribution and Radial Extent. *Astron. J.*, **122**, 1051-1066.

Petit J-M, Gladman B, Holman M, Kavelaars JJ, Scholl H (2004) The Kuiper Belt's luminosity function from $m_R = 22 - 25$. *AAS/Division for Planetary Sciences Meeting Abstracts*, **36**

C. Wide-field searches for Moons of the Outer Planets

In addition to our searches for KBOs, we are completing the inventory of the outer solar system by search for faint satellites of the outer planets. In July 1999 we conducted a search for Uranian and Neptunian moons at the CFHT. Our efforts were rewarded with the discovery of three new irregular satellites of Uranus. Through the fall and winter of 2000 we conducted a wide-field search for Saturnian moons using a variety of observing platforms. This resulted in the discovery of 12 new Saturnian irregular satellites. One of the most intriguing results of those discoveries is the clustering in orbital elements that can be seen. Just as the Jovian irregular satellites showed inclination families, now Uranus and Saturn show similar families. Own analysis suggests that the smaller members of each family are collisional fragments of the biggest member.

Gladman B, Kavelaars J, Holman M, Nicholson P, Burns J, Hergenrother C, Petit J-M, Marsden B, Jacobson R, Gray W, Grav T (2001) Discovery of 12 satellites of Saturn exhibiting orbital clustering. *Nature*, **412**, 163-166.

D. Pencil-beam Searches for faint Jovian Moons

Four nights were spent in February 2003 at the 4m Mayhall Telescope at KPNO using the 8k mosaic CCD searching for faint Jovian moons using the pencil beam technique. Poor conditions and bad weather limited our search, but a number of possible candidates were found. Bad weather during follow-up runs made us unable to confirm the candidates. We intend to resurvey the fields during the next Jovian observing season using the MMT 6.5m

Telescope with the new MegaCam mosaic camera.

E. Physical Studies of the Irregular Satellites

We used the 2.56m Nordical Optical Telescope and the 6.5m MMT and Magellan telescopes to perform a BVRI survey of the brighter Jovian and Saturnian irregular satellites to test the clustering due to fragmentation hypothesis. In total we performed photometry of 13 Jovian and 8 irregular satellites, demonstrating that most of the clusters indeed have homogeneous broadband colors. We have also acquired near-infrared data with the 8m Gemini and have been awarded one night at the 10m Keck II telescope to further investigate the broadband optical and near-infrared colors of the irregular satellites.

We have also taken data with the 4m CTIO and the 48" FLWO telescopes to investigate the rotational properties of the irregular satellites Nereid and Phoebe. Using data taken during our 2001 and 2002 pencil beam survey of Neptune we were able to accurately determine the rotational period of Nereid. Its short period ($P = 11.52 \pm 0.14$hr) implies that Nereid is almost certainly in a regular rotational state, rather than the chaotic rotational state suggested by other authors.

During a four night run in Jan 2003 we collected BVRI lightcurve data for the Saturnian irregular satellite Phoebe. The data is being reduced and will help us understand how the different surface compositions of Phoebe (which has a range of albedos from 0.06 to 0.11 across its surface) affect the colors of the satellites as it rotates. Phoebe is a target for the Cassini mission and understanding how the brightness of Phoebe varies with rotation in all filters will help determine the exposure times needed to maximize the scientific return of the brief encounter between the space craft and the irregular satellite.

Grav T, Holman MJ, Kavelaars JJ (2003) The short rotation period of Nereid. *Astrophys. J.*, **591**, L71-L74.

Grav T, Holman MJ, Gladman BJ, Aksnes K (2003) Photometric survey of the irregular satellites. *Icarus*, **166**, 33-45.

F. Astrometric Follow-up Observations

The discovery of Kuiper belt objects and outer planet satellites is of little use if the discoveries are not followed by systematic, repeated astrometric observations that permit reliable estimates of their orbits. This inglorious task is necessary to achieve the scientific goals of our program and more than half of the observing time awarded has been dedicated to follow up observations.

2000 CR105 is one of the objects we consistently tracked over the course of years. Its large semimajor axis (216 AU) and eccentricity (e=0.8) indicate that it is a scattered disk object, however its large perihelion distance (q=44 AU) is larger than any other known scattered disk object. Our analysis suggests that the scattered disk has an extended component comprised of such large perihelion objects. Without our recovery and follow up efforts, this object would likely have been lost since its final orbit is significantly different from that initially assumed.

Gladman B, Holman M, Grav T, Kavelaars J, Nicholson P, Aksnes K, Petit J-M (2001) Evidence for an extended scattered disk. *Icarus*, **157**, 269-279.

II. Relevance to NASA Objectives

Obtaining a more complete census of the Kuiper belt is directly relevant to increasing our understanding of how our solar system formed and has evolved. Furthermore, the results of our investigations will contribute to the planning for the New Horizons mission.