The Kuiper Belt

Jonathan Lunine

Reference: Luu, J.X. and Jewitt, D.C. 2002. ***Ann. Rev. Astron. Astrophys.*** **40, 63-101.**

(1) Statement of the problem

The Kuiper Belt is roughly defined as that region of the solar system from the orbit of Neptune (30 AU) out to 100 AU or so, within which nearly 700 objects (as of spring 2003) exceeding 100 km in size have been detected. (The Belt is sometimes referred to as the trans-Neptunian region, or the Edgeworth-Kuiper Belt, although Kuiper Belt is the dominant name in the current literature). An additional hundred or so bodies on highly elliptical orbits that cross this region (Scattered Objects), or which dynamically likely were once part of this region (Centaurs) have been detected. In addition, many if not all of the so-called short-period comets (periods < 200 years) likely had their origin in the Kuiper Belt, and represent the detectable (via proximity) subclass of what may be an enormous number of such bodies in the 30-100 AU region.

The Kuiper Belt is the remnant stable or quasi-stable population of planetesimals on orbits such that ejection by interaction with Neptune will not occur on solar system timescales. As such, they stand with the asteroid belt as one of the two “archeological sites” where the nature of planet-building material may be examined. Kuiper Belt objects, however, are distinguished by being much more numerous than main belt asteroids, and being much colder and hence containing water ice and other volatiles, which are the raw materials of the giant planets and their icy moons. The two problems to be addressed by GSMT are (a) to complete the inventory of Kuiper Belt objects to a much deeper magnitude limit and (b) obtain spectra that will determine the nature of the volatile surface components and determine whether multiple subclasses of these objects exist.

(2) Status of current understanding

Observations coupled with modeling suggest that roughly 10^5 objects exceeding 100 km in diameter exist in the 30-100 AU region, with a total population inclusive of the smaller bodies some 1000 times larger than the asteroid belt. Yet, calculation of the original solar-composition mass density of material implied by this disk falls short of the smooth extrapolation from the giant planet region by several orders of magnitude. Evidently, like the asteroid belt, the Kuiper Belt has been cleared of all but a small fraction of the original material present there. What remains has been dynamically “sculpted” by the gravitational fields of the giant planets (mostly Neptune) in a sequence of interactions beginning with the formation (and possibly small outward migration) of the outermost giant planets, followed by long-term perturbations on the belt that have cleared material from dynamically specific locations.

Efforts to distinguish different dynamical classes of Kuiper Belt objects (KBO’s) from telescopic observations and theory have led to identification of three different types. The resonant KBO’s in definite small number resonances with Neptune (2:1, 3:2, and 2:1) in orbits with semi-major axes from 36 to 48 AU, and modest eccentricities. Those orbiting in the 3:2 resonance are most numerous, and are called Plutinos after the largest-known member, Pluto. All these bodies have perihelia with 30 AU, and hence cross the orbit of Neptune. Their stability depends on being in resonance with Neptune, phased so that close-encounter and ejection does not occur. They are the remnant of a larger population not so gifted with the right orbital elements.   The classical KBO's comprise roughly 2/3 of the known objects in the Kuiper Belt, are defined as having semi-major axes between 42 and 48 AU, small eccentricities and perihelia beyond 35 AU. The scattered KBO's are a minority in the observable belt but could be as numerous as the classical KBO's. They have large eccentricity, large inclination and may represent a population of material originally near to Uranus and Neptune but then scattered outward by these giant planets. Many more may exist beyond 50 AU semi-major axis but are simply not observable with present telescope technology.

The current picture of the structure and evolution of the Kuiper Belt suffers from a number of ambiguities associated with observational limitations. (I) We do not know unambiguously the physical sizes of all but the largest two or three Kuiper Belt objects because we cannot resolve their disks nor separately measure their albedos. It is necessary to detect the thermal infrared signatures of these bodies, or directly resolve disks with larger telescopic/AO systems, in order to determine physical radii. The size-frequency distribution of the various KBO populations is an important constraint on the evolution of the Kuiper Belt, because it is a result of processes such as accretion and collisional grinding-down of bodies. Determining a different size-frequency distribution for the classical and resonance bodies versus the bodies in the scattered disk would be of extreme importance and might tightly constrain the origin of the scattered disk.

(II) The classical disk seems to be truncated at around 50 AU; that is, bodies with semi-major axes smaller than that value not associated with the scattered disk seem to be absent. This seems not to be an observational effect, unless the typical sizes of objects or their albedos decline significantly beyond 50 AU. More plausible is that the classical disk is truncated, but it is unclear how or when this happened. Much deeper surveys with more sensitive telescopes could more severely test the inference that the disk truncates beyond 50 AU, as well as search for objects in the scattered disk to a level of completeness not possible with current systems.

(III) Disagreement exists over whether the distributions of colors among KBO's represents a random and smooth variation, or whether there are distinct classes (i.e., dark/red and bright/neutral)—and further, whether the distinct classes are correlated with the dynamical classes. This issue could be partly resolved through more sensitive photometry, and the independent detection of a thermal signature enabling the albedo to be extracted from the brightness in the optical. Regardless of whether there are two or more "color" classes of Kuiper Belt objects, the existence of broad color variations is itself interesting. Absent other processes, the cosmic ray bombardment of a Kuiper Belt object will tend to darken its surface and, if organics are present, make it very red and very dark. A bright neutrally-colored surface suggests some resurfacing process, perhaps collisions that flake off the dark crust to expose fresh water ice, methane, ammonia, nitrogen, etc., to space. Pluto, and even more so Triton (likely a KBO captured by Neptune early in the history of the solar system), exhibit bright areas that are the result of seasonal resurfacing by volatile ices as the subsolar point moves across their surfaces. Smaller KBO's may not be able to stably retain the vapors of volatile ices like methane and nitrogen, but exposure by collision of new pockets could be followed by cycles of sublimation and condensation with progressive removal of the exposed material, along with cosmic-ray-induced darkening. Unfortunately, near-infrared spectra to determine the presence of hydrocarbons, nitrogen-based compounds and water ice is extremely difficult given the small sizes and distances of KBO's. Only Pluto, its moon Charon, Triton, and a couple of smaller KBO's show spectral features, and only on the first three can quantitative analysis of surface composition be made—even at the world's largest existing telescopes.

(IV) Comparison of the composition of the surface ices on bright Kuiper Belt objects is crucial if we are to connect the short-period comets to an origin in the Kuiper Belt. Also, comparative spectra of grains in comets and extrasolar disks that are remnants of planet formation weakly suggest compositional similarities. Since the Kuiper Belt itself is a better analog for the dust producing material in such disks than are the individually scattered comets (which are extremely evolved dynamically), similar comparisons between disks and KBO's are highly desirable—but will require very large telescopes for the KBO spectra.

(3) Description of key measurements needed

Here the key measurements required are organized along the lines of the four problems (I,II,III) described above.

(I) Detection of thermal infrared signatures of KBO's will be difficult for GSMT, especially compared to space-based cold telescopes like JWST, but GSMT might determine directly albedos for some of the nearer KBO's by direct AO detection of the disk. Thus both high precision AO and infrared measurements on individual objects are desirable with GSMT.

(II) Deep optical surveys of the Kuiper Belt to detect more distant, and smaller objects, will be a key capability of the GSMT. Long exposures to achieve V magnitudes of XX so as to detect a 10 km, albedo 0.1 object at 100 AU are important, but such pencil-beam surveys may miss objects with unusual orbital inclinations, and so broader but shallower surveys are desirable as well. KBO's with 10-km radius in orbits like those of the 100 km sized bodies discovered to date will be well within reach of GSMT.

(III) Precision photometry of Kuiper Belt objects to better constrain colors on already-measured objects, and to obtain colors on fainter or hitherto unknown objects, is required to resolve the relationship among color/brightness /dynamical class. In particular, analyzing color properties for a large cohort of scattered disk objects will require the high sensitivity of GSMT.

(IV) Spectroscopy in the near-infrared, despite extensive work on Pluto and Triton, really remains an unexplored frontier for the majority of KBO's, those observed to date having no or low S/N features. GSMT's high sensitivity should enable R=1000 spectroscopy on small Kuiper Belt objects. Figure 1 shows a simulated spectrum of a 20 km radius KBO at 30 AU assuming a surface composition akin to Pluto, for the sake of argument. Corresponding sensitivities of GSMT are given at three wavelengths for R=1000 spectroscopy/ GSMT can measure the spectrum of this very small object. Equivalently GSMT can do the same for the 100 km sized bodies more typical of what is detected today, at larger distances (100 AU) or lesser brightness than the putative object modeled here.

(4) Comparison with JWST and SIRTF

As cold space borne telescopes, JWST and SIRTF will do a better job than GSMT of detecting and measuring the thermal infrared signatures of KBO's, which have surface temperatures of 30-50 K (or less), and hence Planck peaks in the 60-100 micron region. (Although SIRTF goes to much longer wavelength than JWST, the latter's larger mirror aperture makes it more sensitive for these detections). Conversely, GSMT will be a much better survey instrument for detecting smaller or more distant KBO's in the optical than will be either JWST or SIRTF, because of GSMT's enormous mirror area. It should also beat either infrared telescope in obtaining resolved disk observations of closer KBO's via the large aperture and advanced AO.

Color photometry with GSMT will likely outshine that of NIRCam (JWST) photometry, again because of signal to noise. However, spectroscopic capabilities of GSMT and JWST will be complementary. The high sensitivity of GSMT in the optical will enable good resolution spectra in the near-IR of objects 1% the radius of Pluto, but at wavelengths approaching 5 microns these objects will be extremely dark as a result of the lack of solar flux and the lack of significant thermal flux until the mid-infrared is reached. The mid-infrared spectra will best be done with MIRI on JWST, because of the cold space telescope's enormous depression of the parasitic infrared background. The mid-infrared spectra of KBO's, including Pluto and Charon, are unknown territory; even Voyager 2's flyby of Triton did not yield such a spectrum because the infrared instrument onboard was optimized for Jovian and Saturnian temperatures and was limited to broadband radiometric mapping at Triton. Thus, such spectra will be exciting in their own right. But the near-IR spectra obtained from GSMT for KBO's other than Pluto will likely contain important surprises, since we really do not know the range of surface compositions that obtain the Kuiper Belt. Such spectra, of multiple objects, will permit meaningful comparisons with cometary and remnant circumstellar disk compositions.

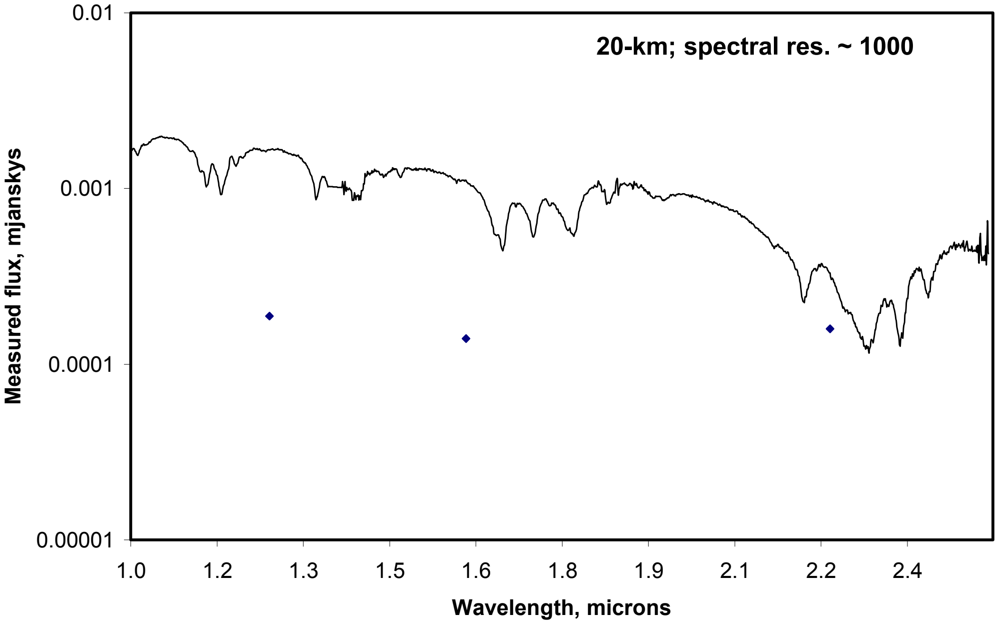

Figure 1. Model spectrum of a KBO 30 AU from Earth, with radius 20 km and an overall albedo similar to Pluto's, plotted as millijansky versus wavelength. The shape of the spectrum is taken from that of Pluto's reflectivity versus wavelength, courtesy John Stansberry, then convolved with the solar flux at 30 AU. KBO's are expected to have a wide range of possible spectra; some are known to be relatively featureless and red. The sensitivity numbers, courtesy M. Mountain, are for a 10^4 second exposure, S/N=10, with 4 x 4 pixels across the point source and a GSMT emissivity of 10%.