THE KUIPER BELT: OVERVIEW

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The study of the Kuiper Belt has emerged as one of the leading subjects in planetary science. The Kuiper Belt offers many intriguing clues to the nature of the early solar system, and may also reveal key information about the processes behind the formation and growth of planets in the accretion disk of the sun. Kuiper Belt science has already been reviewed in detail several times elsewhere in the astronomical literature. In this short overview paper, I separate those aspects of the Kuiper Belt which are known with considerable confidence from other aspects that are less well known. In this way, I hope to provide a context for the other papers presented at the ESO Minor Bodies Workshop. To save space, and in the interests of keeping a tight focus on the subject at hand, I omit source references from this overview. The reader is directed to two full length reviews for complete references to the research literature (Jewitt, Annual Reviews of Earth and Planetary Sciences, 1999; Jewitt and Luu, Protostars and Planets IV, 1999). Both are available at *http://www.ifa.hawaii.edu/faculty/jewitt/papers/*.

1 Things We Know About the Kuiper Belt

i Existence

The existence of the Kuiper Belt has been firmly established since the first direct observations of Kuiper Belt Objects (KBOs) starting in 1992. The possibility that objects might be present beyond Pluto was the subject of published speculation by Kenneth Edgeworth as early as 1943.

ii The name is controversial

Edgeworth's publications were not cited by his more famous contemporary Gerard Kuiper who, in 1951, wrote a review paper that included speculation about objects beyond Pluto (which he believed to be a massive planet in its own right). Perhaps in retribution, some have suggested that the Kuiper Belt should instead be named for Edgeworth. The hybrid (but clumsy) Edgeworth-Kuiper Belt is also sometimes used, as in the present Proceedings. In fact, neither Edgeworth nor Kuiper predicted the key features (numbers, sizes, masses, orbital properties) of the objects we now know to populate the outer solar system. Indeed, neither possessed a physical theory capable of making such predictions. For this reason the more descriptive appelation Trans-Neptunian Belt is sometimes used.

iii Sample statistics and population estimates

At the time of writing (March 1999) 130 KBOs have been reported. Of these, approximately 50 have been observed at more than one opposition, and thus possess reasonably secure orbital elements. A complete and frequently updated list of KBOs is maintained by the Minor Planet Center at *http://cfa-www.harvard.edu/cfa/ps/lists/TNOs.html*.

The cumulative sky-plane surface density, Σ [deg^{-2}], can be fitted by a power law

$$\log\Sigma = \alpha\,(m_R - m_o)$$

where α and m_o are constants and m_R is the apparent red magnitude. Published estimates of α lie in the range 0.58 to 0.7, while unit surface density is reached at $m_o = 23.3 \pm 0.1$. The cumulative surface density increases by a factor $10^{\alpha} \sim 4$ mag^{-1} to 5 mag^{-1}. The surface densities of KBOs brighter than $m_R = 21$ and fainter than $m_R = 26$ are not well constrained.

Most of the known objects have been discovered in narrow field-of-view surveys made using telescopes of moderate (2-m) to large (10-m) aperture. Estimation of the Kuiper Belt population is subject to considerable uncertainty, due to bias effects in the data. Specifically, the surveys are flux limited, not volume limited, meaning that large and nearby KBOs are more readily detected than small and/or distant ones. The intrinsic population must thus be inferred from the survey data using models of the spatial and size distributions in the Kuiper Belt. From such models, the number of objects larger than diameter $D = 100$ km is found to be $N(100\text{km}) \sim 10^5$, in the $30 \leq R \leq 50$ AU range. By extrapolation, $N(5\text{km}) \sim 10^9$, with an uncertainty of at least an order of magnitude.

iv Dynamical groups

The orbital elements of KBOs are divided into three distinct groups. The majority (~2/3) are "Classical KBOs", with semi-major axes $42 \leq a \leq 50$ AU and modest eccentricities ($e \sim 0.1$) that help them maintain a large separation from Neptune even when at perihelion. About 1/3 of the known objects are located in mean-motion resonances with Neptune (most in the 3:2 mean motion resonance at a = 39.4 AU). These are the resonant objects or "Plutinos", which seem to be dynamical counterparts of Pluto. A single object, 1996 TL66, is neither Classical nor resonant, and is the prototype of the third dynamical category. The Scattered KBOs possess large semi-major axes, eccentricities and inclinations but have perihelia within ~5 AU of Neptune, to which they are weakly dynamically coupled.

v Inclination distribution

The apparent distribution of orbital inclinations has FWHM = 10 ± 1 deg. Six KBOs have $i \geq 30$ deg, and one (1999 CY118) has $i = 41$ deg. Observational selection effects discriminate against objects of high inclination and, therefore, the apparent FWHM must be a lower limit to the intrinsic width of the inclination distribution.

vi Velocity dispersion

The root mean square inclinations and eccentricities of KBOs indicate a velocity dispersion $\Delta V \approx 1$ km /s. Collisions between all but the largest KBOs should be erosive rather than agglomerative.

vii Discovery distances

The distances at which KBOs are discovered fall in the range $26 \leq R \leq 48$ AU. The eight KBOs so far discovered with $R \leq 30$ AU are Neptune-crossing Plutinos.

viii Size distribution

The size distribution is consistent with a differential power law having index $q \sim -4$, with an uncertainty of about ±0.5, in the diameter range $100 \leq D \leq 2000$ km. Few objects smaller than 100 km have been sampled with observational confidence. The largest known KBO is Pluto (D = 2300 km). The largest discovered in the modern era is 1996 TO66 ($D \sim 800$ km assuming surface albedo $p_R = 0.04$).

ix Mass

The mass in observable objects ($D \geq 100$ km) is of order 0.1 M_{Earth}. The primary uncertainty in this estimate results from the unmeasured albedos of KBOs. The derived mass is proportional to albedo$^{3/2}$. Crude dynamical limits to the Kuiper Belt mass of ~ 1 M_{Earth} have been placed based on the long-term stability of the orbit of comet P/Halley and on the absence of perturbations to spacecraft passing through the Belt.

x Colors

The optical colors range from neutral to red, with a dispersion that exceeds the uncertainties of measurement. Compositional diversity, at least of the surface layers, is thus implied. The reddest KBOs are coated by a material that is not observed elsewhere in the solar system, except on the surfaces of some Centaurs (which are themselves recent escapees from the Kuiper Belt). Collisional resurfacing has been suggested as a possible cause of the color dispersion. According to this hypothesis, the instantaneous surface color results from a competition between reddening due to cosmic ray damage and resurfacing by fresh, unreddened material due to sporadic impacts.

2 Things We Think We Know

i Cometary reservoir

Dynamical considerations indicate that the short-period comets are more probably derived from a flattened source than from a spherical source like the Oort Cloud. It is suspected that the Kuiper Belt is this source. The inferred number of small KBOs, N(5km) ~ 10^9, is probably sufficient to supply the short-period comet flux over the age of the solar system. However, detailed comparisons between the cometary and Kuiper Belt populations are severely impaired by the near absence of direct measurements of the sizes of these objects. The median size of the nuclei of short-period comets, for example, is very poorly determined, while the sizes of KBOs are based on assumed, not measured, albedos. Neither is it clear from where in the Kuiper Belt the short-period comets originate. Chaotic zones near resonances and the scattered KBO population have both been suggested as sources.

ii Formation

It is likely that Kuiper Belt Objects inside ~40 - 45 AU formed before Neptune reached its current mass, since disturbances by Neptune would magnify the velocity dispersion among planetesimals in the adjacent disk and so impede collisional coagulation. The formation time for Neptune is uncertain, but possibly of order 10^8 yrs.

Models of planetesimal accumulation suggest that the present mass of KBOs is too small to allow formation of even 100 km sized objects in 10^8 yrs. Initial Kuiper Belt masses near 10 M_{Earth} to 30 M_{Earth} (i.e. 100 times the present mass) are needed to guarantee formation of KBOs up to and including Pluto-sized bodies in 10^8 yrs or less.

iii Dust

Impacts onto the Voyager 1 and 2 spacecraft when beyond 30 AU are plausibly ascribed to micron-sized dust particles generated in the Kuiper Belt. The optical depth in micron-sized particles is $\tau \sim 10^{-7}$, about 4 orders of magnitude smaller than the estimated optical depth of the β Pictoris dust disk. The production rate of micron-sized dust particles implied by the Voyager detections is near 10^3 kg s^{-1}. This is close to the dust production rate expected from erosion of KBOs by interstellar dust particles.

iv Colors

There is evidence that the optical colors of KBOs might be bimodally distributed. If confirmed, a bimodal distribution would eliminate collisional resurfacing as a plausible cause of color diversity in the Kuiper Belt.

v Spatial distribution

The flux-limited longitudinal distribution of KBOs should vary with angular separation from Neptune. The Plutinos, for example, reach perihelion near ±90˚ from Neptune, and should be overabundant in these directions relative to others. Like Pluto, they may also occupy the "argument of perihelion libration", which maintains perihelion at non-zero ecliptic latitude and therefore further minimizes Neptune perturbations. Longitudinal structure is apparent even in existing surveys but variations with latitude have not been adequately sampled.

vi Constraints from Pluto

The large specific angular momentum of the Pluto-Charon binary is often taken as evidence that Charon was created by a giant impact into Pluto. However, the specific angular momentum remains somewhat uncertain, pending accurate determinations of the density of Charon. The density of Pluto (about 2000 kg m^{-3}) indicates a large rock fraction, but it is unlikely that this density is representative of smaller KBOs. The densities of cometary nuclei (small KBOs?) are highly uncertain, but probably near 1000 kg m^{-3}.

vii Other Plutos

Models fitted to the measured sky-plane surface density of KBOs allow the possibility that other Pluto-sized objects await discovery in the Kuiper Belt. All published surveys, including Tombaugh's original, admit this possibility. Detailed accretion models by Scott Kenyon and Jane Luu typically produce a handful of Pluto-sized objects, rather just a single example. More Plutos may soon be discovered in surveys directed towards large areas and bright limiting magnitudes.

3 Things We Would Like to Know

i How were the resonances populated?

Radial migration of the planets (and their resonances) in response to torques exerted on the planetesimal disk can lead to trapping provided a) the migration is outward, smooth and slow and b) the planetesimal disk is initially cold (low initial inclination and eccentricity). As developed by Renu Malhotra, this attractive "resonance sweeping hypothesis" makes observationally verifiable predictions about the structure of the Kuiper Belt. The most eccentric Plutinos ($e \sim 0.34$) indicate that Neptune migrated radially by ~7 AU, possibly on a timescale of a few million years.

If Neptune did not migrate appreciably, or if its drift were inwards rather than outwards, then the resonant populations are less easily understood. It has been suggested that KBOs, weakly scattered by massive interlopers, were captured in proportion to the small fraction of phase space occupied by resonances.

ii What was the initial mass of the Kuiper Belt?

As remarked above, the long growth times of KBOs suggest formation in a disk containing perhaps 100 times more mass than in the present Kuiper Belt. A similar factor is obtained by simple extrapolation of the smeared surface density of the planetary disk, as determined from the masses of the major planets. Are these estimates realistic, or is some crucial aspect of planetesimal agglomeration missing from our characterization of the problem?

iii How was the mass lost?

Collisional grinding (in which large KBOs collide and shatter into smaller and smaller particles, eventually to be removed by radiation forces) has been suggested but not yet realistically modelled. For example, even at the present inclinations and eccentricities, the larger (diameter ≥ 100 km) KBOs cannot be collisionally shattered. What was the distribution of collisional velocities in the epoch when collisions were supposedly dominant? The Plutinos, which are very weakly bound to the 3:2 mean-motion resonance, do not look like a population that has been heavily collisionally modified. Indeed, even modest collisions would preferentially eject these objects from resonance.

Ejection by massive (Earth-mass?) projectiles has been suggested but, to date, not explored by means of a realistic numerical simulation. Could massive interlopers clear 99% of the mass of the primordial Kuiper Belt? What specific, observationally verifiable predictions are made by this hypothesis?

A 100 times more massive Kuiper Belt would presumably generate a flux of short-period comets 100 times that presently observed. Is there evidence in the early cratering records of the surfaces of planetary bodies for this elevated flux? Could the terminal bombardment phase of the inner solar system's first 0.5 Gyr be due to clearing of the massive Kuiper Belt?

iv How were the classical orbits excited?

The same hypothetical Earth-mass projectiles might have excited the inclinations and eccentricities of surviving classical KBOs. The scattering is achieved by carefully selecting the number, masses and orbital trajectories of the projectiles. The survival of the resonant KBOs under perturbations from massive projectiles capable of ejecting the Classical KBOs seems unlikely.

v What role have collisions played in shaping the belt?

The widely held belief that the Kuiper Belt is a collisionally evolved system is based on large extrapolations of the measured KBO population. In fact, the observed KBOs have mutual collision times that are vastly in excess of the age of the solar system: they constitute a collisionless system! What is the present day collision rate in the Kuiper Belt? The answer depends on a careful assessment of the small body population since, in a $q \sim -4$ distribution, the cross-section lies with the smallest objects. The Taiwan-America Occultation Survey is uniquely sensitive to small KBOs and, hopefully, will soon throw light on this question
(see *http://taos.asiaa.sinica.edu.tw/*).

vi What are the albedos?

Other than ISO measurements of marginal ($< 3\sigma$) statistical significance, there are no detections of thermal radiation from KBOs. Knowledge of KBO sizes and albedos is therefore confined to measurement, from optical data alone, of the product of albedo with the geometric cross-section. Measurements of related objects (nuclei of short-period comets, Centaurs) support the assumption of generally low visual albedos near 4%. It is possible, however, that some (many?) KBOs have much higher albedos. Indeed, the largest KBO (Pluto) retains surface frosts that convey an albedo near 60%. Do reflective frosts coat the surfaces of other KBOs?

vii What is the radial extent?

The Kuiper Belt has an *apparent* edge near 50 AU, in the sense that KBOs have not yet been discovered at distances > 50 AU. Whether this is also a physical edge is not clear. Ultradeep, wide-field imaging surveys are needed. Theory provides no useful guide to the expected radial extent of the Kuiper Belt. Neither do observations of external circumstellar disks, some of which are 100's to 1000 AU in extent while others, like some Orion proplyds, are of 50 AU scale.

viii What is the ultra-red material?

Ultra-red matter is present on some KBOs but absent from the inner solar system. Is this matter thermally unstable, or buried (or otherwise hidden from view) by fall-back debris ejected in response to outgassing when near the sun (e.g. in the case of the Centaurs)? What is the chemical composition of the ultra-red material and how was it formed?

ix Is the Kuiper Belt a local analog of dusty disks around other main-sequence stars?

If the Kuiper Belt were once 100 times more massive than at present, was the cometary flux also 100 times greater and was the dust production rate (which scales roughly with the square of the number of colliding particles) fully 10^4 times greater than at present? Are Kuiper Belts produced naturally as products of accretion in circumstellar disks? What is the time dependence of the dust cross-section in our own Kuiper Belt, and in the Kuiper Belts of other stars?