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Forward to the University of Arizona Kuiper Belt Book

Only rarely are we, as scientists and as people, able to witness a whole new research tree grow and blossom from essentially nothing within just a few years, yet this is exactly what has happened with the Kuiper belt since 1992. Those of us whose research has "helped the tree grow", a group which includes most of the authors in this book, share a real and justifiable sense that we are involved in something big, even something historic in the exploration of the Solar system. A milestone has been passed. We have at last moved decisively beyond the domains of the rocky planets and the giant planets into the domain of the comets. Almost everything we find in this third domain is new and surprising: theory has so far been a rather unhelpful guide. But the shock of the new only shows that we are *really* exploring and adds considerably to the allure of the subject. Even better, most of the key work so far has been done by individuals or very small groups, lending a strong personal dimension to the endeavor. No team meetings or group-think sessions for us! As the field develops this will surely change. But, for now, what a privilege and what a thrill it is to be able to do science this way.

The Kuiper belt is amazing in its ability to link together research areas that previously seemed unlinked. Different populations of small bodies used to be described separately and given different labels, like strange animals in an exotic zoo. Now, we see their connections more clearly. The Centaurs are probably escaped Kuiper belt objects. The Jupiter family comets are Centaurs that have run the gauntlet of the giant planets and survived (the more typical fate of such bodies is to be batted out of the Solar system, never to be seen again). Some Earth-crossing "asteroids" are dead or dormant comets recently arrived from the Kuiper belt. Even the Trojans and the irregular satellites of the giant planets could have originated in the Kuiper belt, although convincing evidence for (or against) this possibility is lacking. The context provided by the Kuiper belt shows that the whole system is beautifully interconnected: it has become meaningless to study the different parts in splendid isolation, as we did before. Planetary science will never be the same again.

The Kuiper belt is also a transitional structure that helps us to relate our planetary system to others. We observe dusty disks around main-sequence stars in which the dust lifetime is short compared to the age of the central star. Dust in these "debris disks" cannot be primordial and must be continually supplied from a hidden source if steady-state is to be maintained. Extrapolating from our own system, collisions between unseen extra-Solar Kuiper belt objects constitute a likely source of dust for the debris disks. If so, it is entirely appropriate to think of the Kuiper belt as the Sun's own debris disk. Perhaps in the future we can use the Kuiper belt to help interpret the debris disks, and the debris disks to set the Kuiper belt in a proper stellar context. Planetary scientists and stellar astronomers have something to talk about.

So, what do we really know? A *Forward* like this is not the place to discuss details but I think it is worthwhile to at least present key results from the first ∼15 years of exploration of the Kuiper belt, in the form of a time-line (see Figure). There I have indicated the dates of major observational findings that have changed the way in which we think about the outer Solar system. The scale on the right shows the steady rise in the number of objects known.

The broad inferences from these findings are well known. The resonant KBOs, including the abundant 3:2 mean-motion resonance Plutinos, were probably trapped as Neptune migrated outwards, towards the end of its growth phase. The obvious implication is that the KBOs, including big ones like Pluto and Eris, had formed before Neptune settled in place. While Neptune is not gas-dominated like Jupiter and Saturn, it does contain a few Earth masses of hydrogen and helium that must have been accreted from the rapidly dissipating gas nebula. Observations of disks around other stars show that gas survives only a few (at most ten) million years, and so this sets an upper limit to the time available to grow Neptune and, probably, the KBOs. However, the small (0.1 $M_\oplus$) mass and large extent of the belt imply low disk surface densities ($\sim$0.005 kg m^{-2}, roughly 10^4 times smaller than at the orbit of Jupiter) and unreasonably long (e.g. billions of years) binary accretion growth times for the KBOs, if they formed in place. A possible solution is to form them closer to the Sun where the protoplanetary disk densities were higher, and growth times shorter, and then to transport them out to their current locations (but how?). Another possibility is that growth rates in the Kuiper belt were much higher than is believed because of local concentration of solids ("particle pile-up") from the action of aerodynamic or other non-gravitational forces, but this has yet to be adequately explored. The most direct way to achieve growth times short compared to the age of the Solar system is by increasing the density in the Kuiper belt by increasing the mass. A mass augmentation factor of ∼100 to ∼1000 times is needed, meaning that the primordial belt mass would have been ∼10 $M_\oplus$ to 100 $M_\oplus$ (i.e. in the range of a Uranus or a Neptune, perhaps as high as a Saturn mass). It is interesting that high initial masses are also needed to account for the observed high abundance of Kuiper belt binaries. Specifically, none of the major models for binary formation can operate with the necessary efficiency unless the density of objects started much higher than now.

If these high initial masses can be believed, then the real puzzle (and I think still the most important puzzle) for the Kuiper belt is how 99% or 99.9% of the mass was lost. Collisional grinding and subsequent mass loss by radiation drag seem attractive, because they remind us of processes likely to operate in the dusty "debris disks" of nearby stars. However, the KBO size distribution (a differential power law proportional to $diameter^{-4}$) places a lot of the mass in KBOs too large to have ever been collisionally destroyed, so I suspect this model cannot be the right one. The alternative is dynamical ejection, in which most of the mass is scattered away by a passing star, or careening planets or violent shaking of the Solar system in response to resonant interactions between giants, or some other way. Whatever happened left us with a delicately and remarkably structured Kuiper belt, including populations of resonant, scattered and detached ("extended scattered disk") objects in addition to the classical belt. The unexpectedly sharp outer edge of the classical belt at ∼48 AU may also reflect some destructive process at the end of the clearing phase: there are many suggested explanations for the edge, all of them rather ad-hoc. The clearing process probably also pumped up the velocity dispersion in the belt to its current value of ∼1.7 km s^{-1}. Collisions between KBOs today are erosive, not agglomerative: the Kuiper belt is dynamically very far from the thin accretion disk suggested in some early models.

Beyond the models that try to fit specific features of the Kuiper belt, we are beginning to see attempts to propose "global" models that account for the overall structure of the belt *and* the rest of the Solar system. In one such model, Uranus and Neptune are survivors of a set of ∼five "oligarchs" whose gravitational interaction ejected the others and simultaneously cleared the Kuiper belt. The efficacy of this model appears to be strongly sensitive to the assumed surface density of the protoplanetary disk, working best for very low values. In another model, no doubt described elsewhere in this book, the key destabilizing event is instead assumed to be caused by Jupiter and Saturn crossing the 2:1 mean motion resonance. If it happened, resonance crossing would shake the Solar system, hurling Neptune into the Kuiper belt where it would dislodge most of the mass and shower the planetary region with liberated projectiles.

This model further seeks to fit the late-heavy bombardment (LHB) that is inferred from Lunar data to have occurred 3.8 Gyr ago. Migration into the resonance hence must be delayed by ∼700 Myr after planet formation. In the model, this delay is achieved by making judicious assumptions about the initial orbits of the planets and the magnitude of the torque from the massive primordial Kuiper belt. An everyday analogy for this delayed instability is a pencil balanced on its tip on a flat table top. If the initial conditions (the orientation and initial angular momentum of the pencil about the tip) and external perturbations (vibrations, drag from air currents) are controlled with sufficient precision, the fall of the pencil could be delayed, in principle, for a very long time. (Try this yourself, to get a feel for the fine-tuning required). But it's not easy. Indeed, honest experts disagree about whether or not the LHB occurred at all because of uncertainties inherent in the interpretation of limited and biased samples of Lunar rock. There might have been no LHB "spike" at all, in which case the model, somewhat perversely, would offer us a beautiful explanation of something that did not happen!

So, is figuring out the history of the Solar system a hopeless game of guesswork? It sometimes looks like that, but the answer is a definite "no". The flood of data from the first 15 years of the Kuiper belt has unarguably focussed our attention on important processes (like migration and planet-planet interactions) that were previously more or less ignored. Detector advances (Moore's Law) and better telescopes bring us greater observational power every year. Observations that were at the limits with cameras of 4 Megapixels in 1992 are trivial with 400 Megapixel cameras now. The next step is Pan STARRS in Hawaii (1.4 Gigapixels and a 7 square degree field of view), a precursor to the Large Synoptic Survey Telescope project. Better observations offer us a real chance to finally figure out what's in our Solar system. Better models, when used to cast observationally testable predictions, will eventually show us why it is the way it is.

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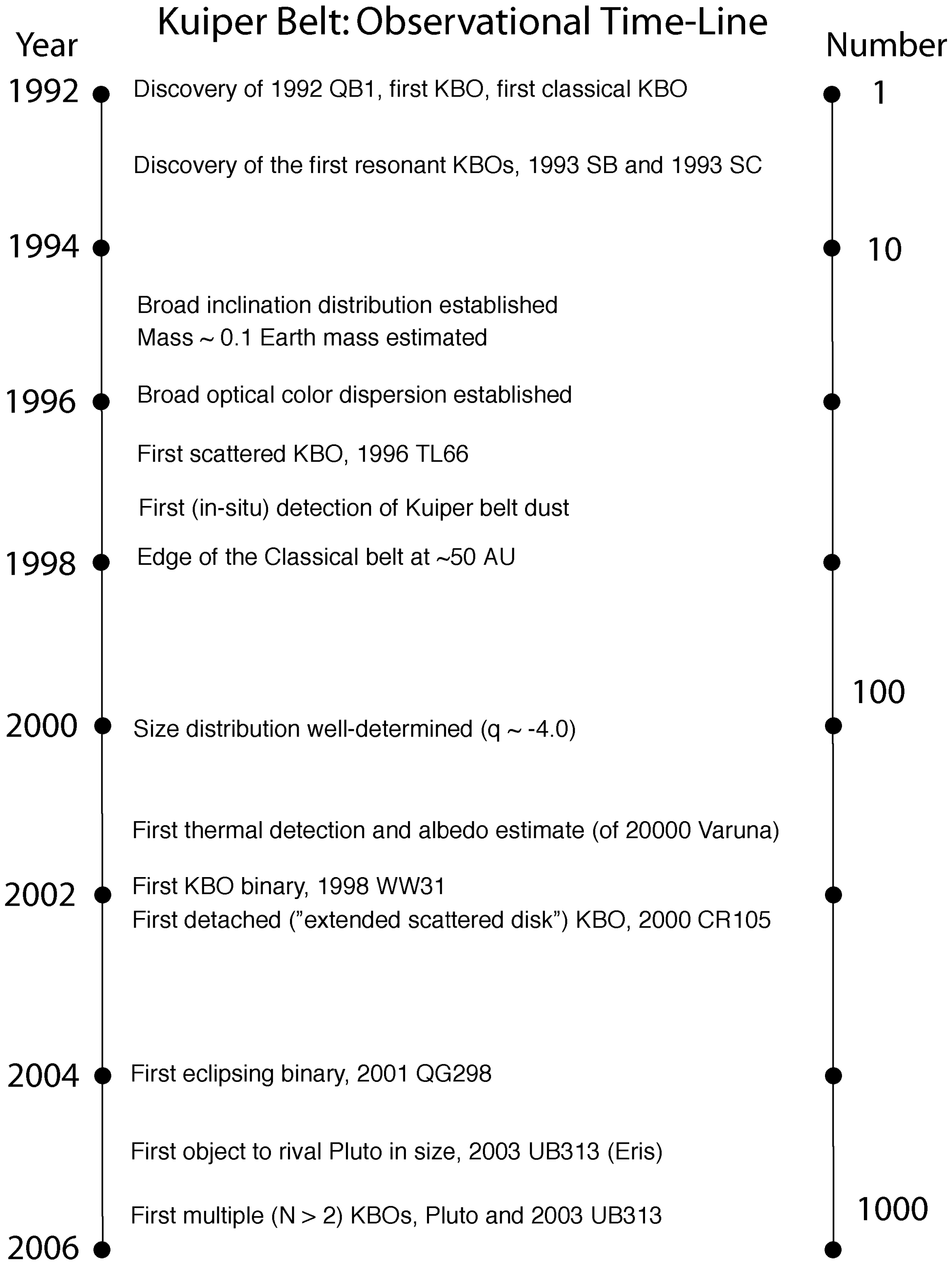
Kuiper Belt: Observational Time-Line
Year
Number
1992
Discovery of 1992 QB1, first KBO, first classical KBO
1
Discovery of the first resonant KBOs, 1993 SB and 1993 SC
1994
10
Broad inclination distribution established
Mass ~ 0.1 Earth mass estimated
1996
Broad optical color dispersion established
First scattered KBO, 1996 TL66
First (in-situ) detection of Kuiper belt dust
1998
Edge of the Classical belt at ~50 AU
100
2000
Size distribution well-determined (q ~ -4.0)
First thermal detection and albedo estimate (of 20000 Varuna)
2002
First KBO binary, 1998 WW31
First detached ("extended scattered disk") KBO, 2000 CR105
2004
First eclipsing binary, 2001 QG298
First object to rival Pluto in size, 2003 UB313 (Eris)
First multiple (N > 2) KBOs, Pluto and 2003 UB313
1000
2006