2012 KAVLI PRIZE LAUREATE LECTURE: TALES FROM THE OUTER SOLAR SYSTEM

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ABSTRACT

The past decade saw an explosion in the discoveries of Pluto- and near Pluto-sized bodies in the outer solar system, giving rise to a new classification of “dwarf planets.” Like Pluto, each of these largest dwarf planets has a unique story to tell about the history and evolution of the solar system. In this lecture, I’ll discuss the discoveries of these objects and the new views of giant collisions, stellar encounters, and atmospheric evaporation that we are gaining from their study.

1. INTRODUCTION

Ten years ago, only a decade after the discovery of the first recognized Kuiper belt object, 1992 QB1, by Dave Jewitt and Jane Luu (Jewitt & Luu 1993), much of the basic structure of the Kuiper belt had been mapped out, and a general outline of the implications of the Kuiper belt for our understanding of the formation and evolution of the solar system was already beginning to become established (see Jewitt Kavli Prize lecture). But during this first decade of discovery, almost all of these newly discovered Kuiper belt objects themselves were such tiny objects – a few 100s of kilometers across at most – that they were generally so faint that, other than where they were and what their orbits told us, we could know nearly nothing of them individually.

The notable exception to these mostly anonymous members of the Kuiper belt was Pluto. Pluto was large enough and close enough to be bright, meaning that it could be studied extensively by telescopes on and off the earth. While the other Kuiper belt objects were just unknowable points of light, Pluto was a little world of its own which told stories of atmospheric freezing and thawing, of a singular gigantic collision between the two largest known objects (at the time), and of ancient ice volcanism (see review in Brown 2002). Much of what we knew – or thought we knew – about the icy objects at the edge of the solar system was derived from all that we could know about Pluto.

It seemed hard to imagine, even at the time, that Pluto was as singular as it appeared. Astronomical surveys searching for objects in the Kuiper belt had been focused on the relatively common and thus much easier to find small objects. Objects of the scale of Pluto would be significantly more rare, and thus would take much more extensive surveys in order to find them.

We began the first such survey in 1998, spending three years covering a vast area of the sky using the comparatively primitive technology of old photographic plates. We found nothing. Undaunted, in 2001 we restarted the survey using the – at the time – largest astronomical digital camera in the world, and, within 8 years, we had covered the entire northern hemisphere, twice, finding nearly 100 objects in Kuiper belt (Trujillo & Brown 2003; Brown 2008; Schwamb et al. 2010). We have recently completed the survey of the southern hemisphere as well (Bannister et al. 2012). One hundred Kuiper belt objects is a small fraction of the ~1500 currently known, but, critically, these are almost all of the large, bright objects which have been found. Especially important, these objects include the dozen largest and brightest objects in the Kuiper belt beyond Pluto (Fig. 1). Like Pluto, each of these objects is bright enough for detailed study from Earth-based telescopes, and, like Pluto, each of these objects contains its own small unique part of the story of the history of the solar system. Together, these largest objects in the Kuiper tell us tales of violent collision, atmospheric disappearance, primordial chemistry, and they may even contain a fossil record of the birth of the sun itself. In this lecture, I will highlight three of the many examples that could be given of what we have learned from these objects.

2. THE NEAR-DESTRUCTION OF HAUMEA

Haumea remains one of the oddest objects known in the outer solar system. It rotates once every 3.9 hours, making it – by a wide margin – the fastest spinning large object known in the solar system. Its rapid rotation has elongated it: one axis has become 1.5 times larger than the spin axis and the other axis 2 times larger, approximately the shape of an American football slightly deflated and then stepped on (Rabinowitz et al. 2006). The
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long axis is nearly 2000 km in length, making Haumea one of first approximately-Pluto-scale discoveries.

The combination of the spin-rate and the shape allows a unique determination of the density (a higher density object would be elongated even more, while a lower density object would be elongated less), giving a result of approximately 2.6 g cm$^{-1}$. This density was significantly higher than that of any other objects known in the outer solar system at the time. Indeed, when both Pluto and Neptune’s moon Triton – which is thought to be an object captured from the Kuiper belt – were found to have densities of approximately 2 g cm$^{-1}$, it was assumed that this value would be typical of everything in the Kuiper belt. A density of 2 g cm$^{-1}$ implies an approximately 70-30 mix of rock and ice, which was then taken as the canonical value for the outer solar system. Haumea’s much higher density suggested a composition of almost entirely rock. Oddly, however, the outer surface of Haumea was found to be covered in almost pure water ice (Trujillo et al. 2007) (Fig. 2), suggesting that it is a highly differentiated body on the inside. The discovery that Haumea also had two tiny icy moons orbiting it (Brown et al. 2005, 2006; Barkume et al. 2006) appeared to strongly suggest a single explanation for all of these unique phenomena, namely, that, early in the history of the solar system, a larger proto-Haumea was obliterated by another massive body, which blasted away much of its icy mantle and left it with a rapid spin. The two satellites would be the only two remnants of the icy mantle remaining; the rest would have dispersed into space.

While this single explanation was compelling, theoretical models of the probabilities of such collisions (often calibrated from the need to form Pluto and Charon) suggested that such a collision was too improbable to have ever occurred in the history of the solar system.

Spectroscopy of some of the other objects discovered in our surveys slowly revealed that a small but significant number of other objects in the Kuiper belt, although they were not nearly the size of Haumea, appeared to share the same unusual abundance of surface ice as Haumea and its satellites. Tellingly, all of these objects with surfaces like Haumea shared orbits similar to Haumea’s (Fig. 3).

The orbital and spectral similarity of these objects is reminiscent of the early observations which led to the discovery of asteroid families, where a single large object was torn apart in a collision which led to the dispersal of a large number of objects with similar composition into nearly-identical orbits in the asteroid belt. The small icy objects that we had found were evidently the icy mantle that had been broken apart in the giant impact we had initially proposed (Brown et al. 2007b). Dynamical simulation even showed that we could use the dispersal of the objects to approximately date when the impact occurred, which appears to be a time early in the formation of the solar system (Ragouzine & Brown 2007). As a check to make sure all of this is not simply a coincidence we have now been able to go back and dynamically predict which objects in the Kuiper belt should be icy fragments from the collision. The predictions inevitably work (Schaller & Brown 2008; Fraser & Brown 2012); we are indeed seeing a family of objects from a single traumatic event near the beginning of the birth of the solar system.

The implications for this nearly catastrophic event are profound, but still being debated. A decade ago Pluto was thought to be unique in having had a giant impact (leading to the formation of Charon and its other moons). We now know similar events have happened to other large Kuiper belt objects, and now that we have recognized the event at Haumea we see the signature of giant impacts for the objects Eris, Quaoar, and perhaps Orcus, too. Having more catastrophic impacts requires more objects to be around or objects to be moving and colliding faster or, perhaps, both. While parts of a plausible explanation for Haumea have been worked out (i.e. Levison et al. 2008), the implications for ubiquitous near catastrophic collision may require significant rewriting of many of our beliefs about the conditions of the earliest solar system.

**Fig. 2.** Reflectance spectroscopy of Haumea from the Gemini and Keck telescopes, compared to a theoretical model consisting of pure water ice. The surface of Haumea appears to be one of the more pure water ice surfaces in the Kuiper belt. From Trujillo et al. (2007).

**Fig. 3.** Orbital parameters of objects in our early spectral survey (Barkume et al. 2008). Objects marked with black or grey symbols have little or no water ice visible on their surfaces, while the group plotted with white symbols have abundant water ice visible on their surfaces. The objects with abundant detectable water ice – which includes Haumea – have similar semimajor axes, eccentricities, and inclinations. The objects are ultimately derived from a nearly catastrophic impact on Haumea which removed almost all of its icy mantle and dispersed it into an orbital cloud in the Kuiper belt.
found something unexpected. Even though most objects in the Kuiper belt probably started with an atmosphere, the vast majority are too small and too hot to have been able to hold on to that atmosphere over the history of the solar system. Only a handful of objects are massive enough or cold enough to still have atmospheres. Of those, Pluto, Eris, and Sedna are the most massive and/or coldest, so they can retain all of their volatiles—nitrogen, methane, and carbon monoxide. Makemake, on the other hand, is just barely large enough to keep its volatiles. In fact, nitrogen, which has a high vapor pressure, should be mostly depleted.

This depletion of nitrogen on Makemake leads directly to the broad methane spectral features. With little nitrogen ice to dilute the methane, the methane ice crystals sinter and grow until they are essentially a glaze covering the surface. The closest terrestrial analogy is to the ghostly blue colors of frozen water in icebergs when most of the scattering ice bubbles have been pressed out and the optical path lengths get long.

Figure 5 shows that two other large Kuiper belt objects straddle the region of complete volatile loss. Quaoar, the first large object found in our surveys, was known to have a surface covered in water ice (Jewitt & Luu 2004), so it could not be covered in methane, and, indeed, it was even hypothesized to have ammonia on its surface, possible signatures of water ice volcanic. More careful reflectance spectroscopy showed that, however, the spectral signature attributed to ammonia was in fact due to a small amount of methane ice (Schaller & Brown 2007a), precisely as predicted (Fig. 6). Quaoar, rather than being an geologically active body, appears to be a cold dead object barely holding on to the remnants of a once vigorous atmosphere.

For years, the fate of the atmosphere of Pluto has been much debated. Will it still exist in the near future or will it freeze out on the surface? Is it robust and ancient or transient and nearly gone? Questions such as these are nearly impossible to answer when the sample of objects with which to compare your object of interest has a size of zero. With our new collection of objects spanning the range from cold to hot from small to big we now have an understanding of atmospheres and their loss and
4. SEDNA AND THE BIRTH OF THE SUN

At the time of discovery in 2003, Sedna was the most distant object that had ever been detected in orbit around the sun. In the first weeks after discovery, we assumed that Sedna was either a typical scattered Kuiper belt object, and thus was near its most distant point from the sun and about to turn inward, or, excitingly, it was a massive enough object to be on a near-circular orbit beyond the planets. Neither turned out to be true. Rather than being near its most distant point, Sedna is near its closest point to the sun (Fig. 7). Its orbit takes it from 76 AU (where an AU – an Astronomical Unit – is the distance from the Sun to the Earth) out to about 1000 AU with an orbital period of more than 10,000 years (Brown et al. 2004).

Such an extreme orbit is difficult to explain. Objects in the solar system generally form on nearly circular orbits – only on such uniform orbits can pairs of objects collide at low velocities, stick together, and grow to the large bodies we see today. After formation, however, smaller bodies having close approaches to larger bodies can be scattered into inclined and eccentric orbits, as seen throughout the Kuiper belt today. Repeated encounters with Neptune can lead to the extremely eccentric orbits of the scattered Kuiper belt objects. While Sedna’s orbit resembles that of the scattered Kuiper belt objects in many ways, in one critical way it is completely different: Sedna never comes close to Neptune. With a closest approach to the sun of 76 AU, Sedna never comes closer to Neptune than the Earth does to Neptune. In fact, Sedna never comes close to any large body in the solar system; nothing that is known to exist in the current solar system is capable of having scattered Sedna to its current location. Of all of the objects known in the entire solar system, Sedna, uniquely, points to the current or past existence of another massive body somewhere in the vicinity.

Many explanations for the cause of Sedna’s unique orbit have been proposed over the past decade (see Brown 2008), including scattering by a yet undiscovered planet, a (highly unlikely) chance stellar encounter, and capture of Sedna from another star’s Kuiper belt. Each of these proposed explanations would lead to a distinct dynamical population of objects in the outer solar system (Fig. 8). Perhaps the most promising explanation to date appears to be that Sedna is a relic left over from the era when the sun was born inside of cluster of stars (Brown et al. 2004; Brasser et al. 2006; Schwamb et al. 2010). In this scenario, Sedna would have formed as a typical Kuiper belt object (or perhaps even a remnant planetesimal formed inside of the orbit of the giant planets) and then quickly scattered onto an eccentric orbit, albeit one that came back to the giant planet which scattered it. Over a few tens of millions of years, however, a series of distant encounter with stars formed in the same cluster as the sun would have changed Sedna’s orbit, perturbing it until its closest point to the sun was well outside the realm of the giant planets. The sun’s birth cluster only stays bound for ~100 million years, however, after which the individual stars disperse into the galactic neighborhood. From this point on, Sedna no longer had any distant encounters with stars, and it was no longer close to any of the giant planets. Nothing could perturb its orbit, and Sedna’s orbit became dynamically frozen, a fossil record of the birth of the sun.

Fossil records are difficult to interpret when there is only one fossil. The full tale that Sedna is telling will only be found when more objects in the same region are discovered. Continual searching for distant objects in this population for the past 9 years has, however, not re-
vealed any other Sedna-like objects. We have used small telescopes to search nearly the entire sky for other unique large objects like Sedna (Schwamb et al. 2009), and we have used some of the largest telescopes in the world to search small patches of the sky for the fainter members of this population (Brown et al. 2012). But, for now, the other members of this population remain frustratingly elusive. New plans are underway to continue the search for this population with telescopes big and small; while these objects may be distant, faint, and difficult to find, it is our hope that – like the case for the first Kuiper belt discoveries 20 years ago – perseverance will eventually lead to a full characterization of this new population of objects in the outer solar system and a chance, perhaps, to finally read this fossil record and begin to tell the tale of the very birth of our sun.

5. ACKNOWLEDGEMENTS

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