Having a Look:
Discovering and Exploring the Outer Solar System

by David Jewitt

(for the book “We Discover”, edited by Marc Gutman: http://www.wediscover.net/how-to-order.html)

1. Discovery

George Orwell wrote that "To see what is in front of one's nose needs a constant struggle,” a statement that is as true in the physical sciences as in Orwell’s arena of social commentary. Scientific discoveries can take many forms, from the unveiling of particular objects, to new classes of object, to finding new phenomena or new physical laws. While some discoveries are expected, others are made because new instrumentation enables a measurement that was not previously possible. Surprisingly often, discoveries occur because we break through a kind of “perception barrier;” something that was unseen in front of us all along is noticed for the first time.

When we’re young, making discoveries comes naturally. That’s because curiosity is the number one survival tool of our species. We’re programmed by evolution to spend our first years filling our brains with countless, practical discoveries about the external world. Childhood is effectively a period of intense discovery that equips us to survive and thrive on a complicated and dangerous planet. These are the roots of science, which clearly stems from our need to understand the threats posed, and the resources and opportunities presented, by the natural world.

Sadly, the older we grow the more likely we are to settle into a comfortable routine that tends to inoculate us from new experiences and so inhibits our ability to explore. Our curiosity begins to slip away. A reasonable aim for the scientist is to try buck this trend of adult life, by maintaining a state of permanent curiosity like the one we all had when we were young. Indeed, the idea of the “scientist as a child,” cheerfully playing with equipment in the lab like a youngster playing with a ball in the garden, is well known, almost to the point of being a cliché. But there is one big and obvious difference: Discoveries by children are personal revelations of things (like talking, walking and throwing a ball) that have already been discovered by others. In contrast, the scientist aims to discover things that nobody else knows. While it’s true that a child-like sense of wonder goes a very, very long way in science (without one, I think you might as well quit), it is equally true that wonder alone is not enough. So what exactly does it take?

2. A Planetary Discovery

I am a planetary astronomer, which means that I use telescopes to examine objects in the solar system to try to figure out new things. My big-picture science motivation is to pin down how the solar system formed and how it has evolved since formation. It's pure science with no economic value, of use only in furthering human understanding of the world. On the other hand, it has immeasurable value for me as a person; research is one of the great pleasures of my existence. Around the world there are probably 100 or 150 planetary astronomers, with most of the interesting new work done by maybe 10 or 15 of them. The name of the game and the thing that distinguishes one astronomer from another, is to know what is worth measuring in the first place. In other words, the key is to ask a good question.

The textbook description of "the scientific method" is that theorists make predictions that observers try to refute. In truth, it's much more messy than that and the tables are often turned: observers make surprising discoveries that theoreticians struggle to capture in their models. Instead of being a deterministic exchange between predictive theory on one side and observational tests on the other, the advancement of science has a large random component. There is absolutely nothing wrong with this. Good science is often about surprises and moments of jaw-dropping astonishment, typically without forewarning from theorists. The way to encounter these surprises and astonishments is to look, loosely guided by an idea, using the best equipment you can find and with the most open mind you can muster. So in my own case, for example, I read the scientific literature voraciously and I certainly try to keep abreast of current ideas. But, in the end, I know that what matters most comes down to a telescope, to luck and to me.

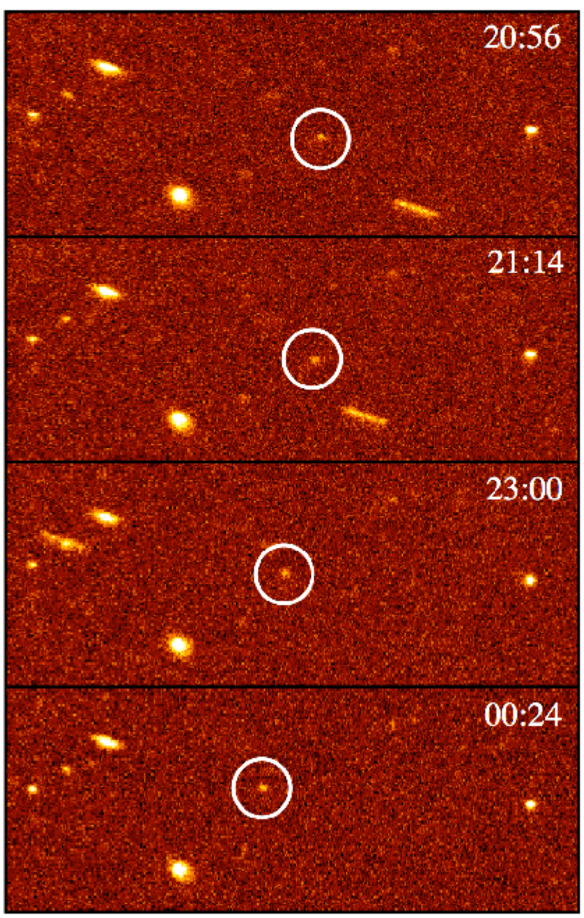
In the 1980s, the inner solar system was known to be home to thousands of asteroids and comets as well as the planets. In contrast, the outer solar system had Uranus, Neptune, Pluto and not much else. This dichotomy between the "empty" and "full" parts of the solar system struck me as peculiar and unnatural. My then-student, Jane Luu, and I reasoned that the emptiness of the outer solar system might be real (because the distant giant planets might have been able to scatter away any nearby objects). Or it might be an artifact; objects viewed in reflected sunlight fade very rapidly (as the inverse fourth power) with increasing distance from the Sun. Perhaps the outer regions were full of objects too far away, too small and too faint to have been detected, given the technology of the day. We didn't know which one, if either, of these possibilities was correct, but the simple question "why is the outer solar system empty?" seemed like a good one. Others before us had asked this same question but did not answer it. We decided that we should try.

• The author at the 4000 meter summit of Mauna Kea, Hawaii (photo credit: Jennifer Gorman)

The only thing to do was to have a look. We set as our goal to find any new objects orbiting the Sun beyond Saturn (which is at 10 AU, or ten times more distant from the Sun than is the Earth). We explored several strategies, but soon settled on the use of CCDs (charge-coupled devices similar to the detectors embedded in modern, electronic cameras) to take multiple pictures of the sky through telescopes pointed in the direction opposite to the Sun. When compared visually on a computer, pictures of a given patch of sky would show moving objects jumping across the image relative to the (fixed) stars and galaxies in the background. In the direction opposite to the Sun, the speed of any moving object should be inversely related to its distance (for the same reason that a high-flying airplane appears to cross the sky much more slowly than a low altitude one, even if they both have the same speed). We sought distant objects, expected to have slow motions relative to the stars. Perhaps a little unimaginatively, we called our project the SMO ("Slow Moving Object") survey.

Video: Explanation of Kuiper Belt in 10 minutes: http://tinyurl.com/KuiperBelt10

We found nothing of interest for over five years until, in 1992, we discovered an object orbiting far beyond anything else in the known solar system. The so-called 1992 QB1 had a nearly circular orbit some 43 AU from the sun (Neptune is at 30 AU) and was about 250 km in diameter (compared with the Earth's diameter of 13,000 km and the Moon's of 3500 km.) This is already larger than almost all asteroids in the main belt between Mars and Jupiter. In the following decade, we continued our survey and found many dozens of trans-Neptunian objects. Our success brought others into the search, triggering an unprecedented avalanche of discoveries in a region now variously called the Kuiper belt or the Edgeworth-Kuiper belt or, simply, the trans-Neptunian belt. At the time of writing, the belt has 1500 known members, and the projected population is several billion objects larger than a kilometer. For every ordinary asteroid in the main-belt there are roughly 1000 Kuiper belt objects beyond Neptune. We had discovered that the solar system beyond Neptune is teeming with primordial objects.

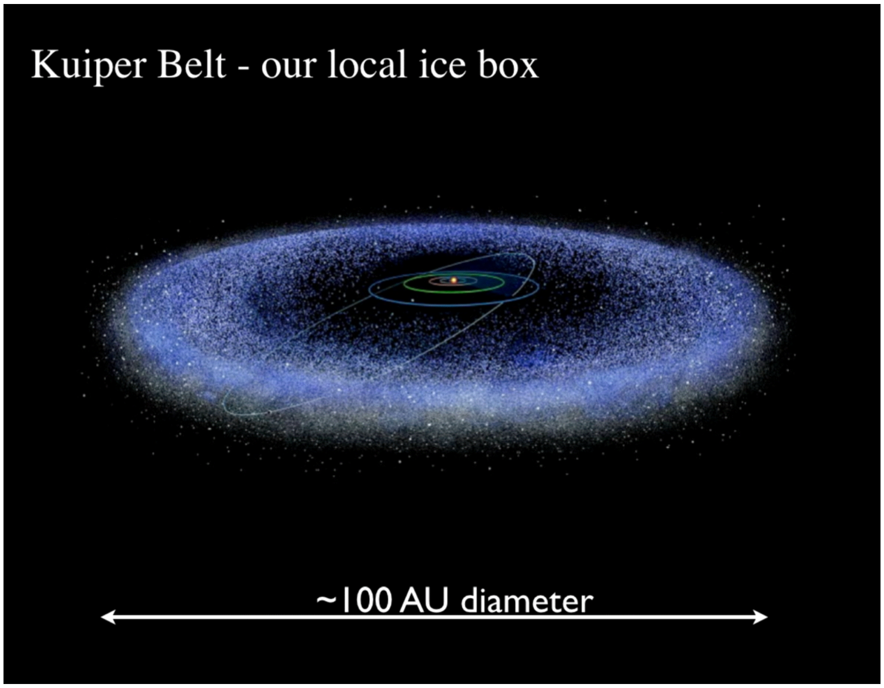


• *Discovery sequence of four images of the first recognized Kuiper belt object, 1992 QB1. The object, circled, drifts slowly to the left relative to the fixed stars and galaxies in the background. The slow motion was the identifying signature that allowed 1992 QB1 to be discovered. The long streak in the first three panels of the figure is a fast-moving small main-belt asteroid, very close to the Earth. It has already left the field by the time of the fourth image. (photo credit: David Jewitt)*

This is not the place to describe in gory detail the scientific significance of the Kuiper belt. Suffice it to say that our discovery has revitalized and revolutionized the study of the solar system, particularly of its formation and evolution. Kuiper belt resolved the long-standing question of where short-period comets come from. It is a repository of the most primitive, least thermally processed matter in the solar system. Comets are aggregates of ice and rock that grew in the frigid outer reaches of our system. Most were ejected from the solar system in an early, chaotic phase, and are lost forever amongst the stars. Some of those that formed beyond Neptune, however, escaped being scattered out and have remained more or less where they formed ever since. The Kuiper belt is essentially a comet nursery. Moreover, temperatures beyond Neptune are so low (-230 Celsius and colder) that there is no chemistry; the original materials accreted 4.6 billion years ago have simply remained frozen there.

• Nucleus of comet Hartley 2, a recent escapee from the Kuiper belt. The nucleus is an ice-dirt conglomerate formed at the beginning of the Solar system and stored in the Kuiper belt deep freeze until recently. Diffuse jets, especially clear near the top of the nucleus, show where ice is vaporized most strongly from the surface. (photo credit: NASA/EPOXI Team)

Our work showed that the motions of Kuiper belt objects fall into distinct groups. For example, the so-called "Classical Kuiper belt objects" (KBOs) have relatively circular orbits aligned in the plane of the solar system. I called them "Classical" because their orbits loosely resembled the classical picture of the primitive solar system that astronomers had developed over the years. Others move in special orbits that allow them to avoid Neptune at all times, even though their orbits sometimes cross that of the planet. I called these "Resonant KBOs" because, in technical language, they occupy "resonances" with Neptune that convey protection from ever meeting the planet. Pluto is a resonant KBO, so I labeled similar KBOs "Plutinos" ("little Plutos") as a tongue-in-cheek way to make the connection memorable. Still others follow vast, looping orbits that pass near Neptune but reach out dozens, hundreds or even thousands of AU. These "Scattered Kuiper belt objects" are in the gradual process of being launched towards the stars by the cumulative effect of repeated gravitational impulses from Neptune.



• Artist's rendition showing the orbits of Jupiter, Saturn, Uranus, Neptune and Pluto. 1 AU is the distance between the Earth and Sun. The orbit of the Earth is too small to be seen at the scale of the figure and the Kuiper belt, if viewed from this perspective by eye, would be too diaphanous to be seen. (photo credit: Don Dixon)

Some of the orbital groups give a dynamical record of the evolution of the solar system showing, for instance, that the orbits of the planets have changed in size since the planets formed. The resonant objects have been especially important in this regard. Planetary dynamicist Renu Malhotra (University of Arizona) showed that KBOs could have been trapped in these special orbits if Neptune had moved outwards from its formation location. Nobody has come up with a better explanation and this "planetary migration" is now a central feature of solar system understanding. Migration has upset the apple cart by destroying centuries-old ideas about a repetitive, clock-like solar system and replacing it with one in which seemingly crazy events might have happened in the distant past. For example, we now recognize that the planets might have experienced an unstable phase in which massive Jupiter and Saturn disturbed each other's orbits, throwing the whole solar system briefly into chaos. As the planetary orbits expanded, their strong gravitational perturbations would have disturbed the Kuiper belt, hurling billions of objects into interstellar space, never to be seen again. Others would have been launched towards the inner solar system, where many would eventually strike the

Sun and planets. And Pluto, formerly the tiniest planet with the largest, most highly tilted and elongated orbit, is now understood as just a large but otherwise ordinary Kuiper belt object.

Lecture: The Significance of the Kuiper Belt - http://tinyurl.com/significancekuiper

Since its discovery in 1992, the Kuiper belt has been discussed in more than 1400 refereed scientific papers, giving some measure of its impact on solar system science.

3. Obstacles

It is fun to consider some of the obstacles we faced on the way to finding the Kuiper belt.

First, we had a very ill-defined target. When we started our survey we didn't know where to expect objects, or how many there might be, or how big or bright, or even if they existed. Our limited aim was simply to find "anything more distant than Saturn," on the understanding that any such object would be interesting because of its uniqueness. Years into the survey, several computational dynamicists wrote papers suggesting that, while the region inside Neptune should have been clear of objects, the space outside might not be. These papers provided moral support for our search, but did not motivate it.

Second, when we started in 1986, we didn't know that the equipment at our disposal was inadequate to the task. Our first telescope was too small and its detector too puny to show the trans-Neptunians. This is obvious in retrospect, of course, but we had no idea at the time. If we had known in the beginning that our instrumentation was incapable of doing the job, we wouldn't have started. Sometimes, ignorance is bliss.

Third, access to telescopes is allocated in a way that does not necessarily encourage discoveries like ours. Observing time is precious and is competitively awarded by impartial committees of other astronomers called TACs (Time Allocation Committees). The telescopes are over-subscribed and many TAC-members want to use the same telescopes for their own projects, so that I sometimes wonder if they are as impartial as they are supposed to be. Even without obvious conflicts, most pre-Kuiper belt astronomers had little interest in the solar system - it was a back-water not a "hot topic" in their minds compared to exciting developments in extragalactic astronomy. That's understandable because, when we started, there was nothing in the outer solar system to be interested in. The TACs at first awarded us less telescope time than we requested, then no time, accompanied by discouraging (always anonymous) comments.

	REVIEWER COMMENT	MY COMMENT
1	"The TAC feels that the...search lacks theoretical grounding and suggests that you involve a dynamicist to explore the stability of this region in the hope of making a stronger case for observing time".	The suggestion is really to use a calculation (which could not even be done using the computers of the mid 1980s) to hold back an observation. In other words, it's an excuse for doing nothing.
2	"The PI has failed to demonstrate that he can do the proposed measurements"	A standard proposal reviewer argument: how can you prove you can do something if you haven't already done it? The answer: you can't! With this way of thinking, how would you ever do anything new?
3	"... the measurements cannot be done with the 88-inch telescope"	Sounds authoritative but, as our discoveries later showed, this is a baseless statement intended to kill the proposal, probably to make time for the reviewer's own project!
4	"This project has been awarded significant time over the past three cycles but has found nothing. How much longer can this go on?"	This is a reasonable question, but with no simple answer. The reviewer is saying that the clock is ticking. Message received.
5	"The proposed limits of the search are inadequate. The author seems unaware of Hal Levison's (unpublished) more sensitive survey. The PI should re-propose with more challenging survey limits."	Using unpublished work to shoot down our proposal is at least unfair and may be unethical (the comment was presumably made by one of Hal's colleagues or friends, using inside knowledge). As success with our survey later showed, the comment is also incorrect.
6	"...this is just a fishing expedition..."	True, but sometimes fishing works.

TAC and Proposal Feedback from my Colleagues

Despite the negativity, the absence of an effective telescope policing system gave us room in which to maneuver. For example, when our telescope proposals were rejected, we responded by requesting observing time for more palatable (i.e. routine) science projects. When allocated, we used the time to do the SMO survey as we wanted. There was nobody on-hand to check what we actually did with the telescope.

Fourth, NASA is the main American source of funding for planetary science research, but it is not designed to encourage our type of discovery. NASA review panels, like TACs, are composed of "peer scientists." Like TAC members, panelists struggle to be impartial because they feed from the same trough. They also tend towards the conservative. NASA panels find it easier to support "incremental science," in which the path to the end is more clear and the result can be confidently predicted. This is not wholly unreasonable; a lot of public money could be wasted on scientific wild-goose chases. To fund a search that had produced nothing, and which might very well continue to produce nothing, evidently seemed to my colleagues on the NASA review panels to be a step too far. My proposals for grant money to support the SMO survey (for example to pay for travel, observing, my students and part of my own salary) were rejected. Out of necessity, I used money allocated for other "incremental science" projects to support the SMO survey. In this sense, the Kuiper belt was discovered despite NASA, not because of it.

• Imagined ice-covered surface of a large Kuiper belt object, with the dim Sun in the upper right. *(image credit: European Southern Observatory/L. Calcada.)*

Any one of these problems (the absence of predictive models, uncertainty about what we were looking for, inadequate equipment, denial of telescope access, denial of funding), could have killed our search for slow moving objects. Even if these hurdles had not existed, there's no law of science that requires the distant regions of the solar system to be occupied. Our system could happily exist without a Kuiper belt and we might have found nothing at all, no matter how hard we had tried. So, the final ingredient contributing to the success of our discovery was "good fortune." We were simply lucky that nature gave the solar system a heavily-populated trans-Neptunian space; it could just as easily have been empty.

People ask why we kept going with the Slow-Moving Object survey, for such a long time without result. The main reason was that we very much liked our own idea; we thought that our question about the emptiness of the outer regions was so simple that it deserved an answer. We knew that "absence of evidence is not evidence of absence" and that "out of sight is out of mind." And we felt that this was a promising subject precisely because other people were not working on it, at least when we started. We also knew that our cameras and computers were steadily improving, a benefit of Moore's Law (according to which the speed of electronics doubles every 18 months or so). As new equipment became available we were able to quickly re-do all the work we had done before and then to surpass it in a fraction of the time. Lastly, as a former long-time user of public transport, I know that the bus always arrives two minutes after you give up hope and walk away from the bus stop. We simply didn't want to give up too soon.

Notes:

My web site includes a general background on Kuiper belt - http://www2.ess.ucla.edu/~jewitt

I've described the discovery of the Kuiper belt elsewhere (D. Jewitt, The Discovery of the Kuiper Belt. Astronomy Beat, Astronomical Society of the Pacific, 2010).

Lecture on solar system science: Planets and Exoplanets: http://tinyurl.com/planetsexoplanets