Standing outside, as the sun sets on the western horizon, one can usually observe multiple objects, including clouds, the sun, moon, the fixed stars, the wandering stars (called planets); sometimes we even catch glimpses of lights streaking across the sky. Each of these objects, now known to be different, had to be separated from the others. In this paper, we will consider how these objects were differentiated from each other, and how the manner in which these objects were differentiated has influenced their categorization. Though it might seem odd, great debates still brew about how to group these celestial objects. In the interests of discussion, this paper will focus on stars and planets, for they have caused the greatest difficulties.

It is almost impossible to understand historical changes without understanding the worldviews that different conceptions were imbedded in. We find that any world view contains a number of assumptions and interrelated concepts that are never jettisoned because a single aspect is discredited.

In the simplest way, the first great division was between atmospheric phenomena and those occurring in the celestial sphere. In the early forms of this, clouds, meteors, and even comets were considered to be atmospheric phenomena. Above the clouds, the celestial world consisted of the sun, the moon, the wandering stars and the fixed stars. Following Aristotle, most individuals believed this diverse group of entities was composed of one substance: aether (Boerst, 2003, p. 23).

Around 450 BCE, based on the fact that the moon shows phases relative to its position to the sun, Empedocles and Anaxagoras determined that the moon differed from other celestial bodies in that its light was reflected light (Kirk, Raven, & Schofield, 1983, p. 156, 300, 381). In a practical sense, this left three classes of objects—the sun, the wandering stars, and the fixed stars—to explain. From the Babylonians onwards, the ancients knew of five wondering stars—Mercury, Venus, Mars, Jupiter, and Saturn—though it was not known how the wandering stars differed from the fixed (Condos, 1997, p. 169)[1]. At some point, the wandering stars were given individual names. Through from what we can gather, it appears that the planets we know as Venus and Jupiter were first identified as separate planets, followed by Saturn and then Mercury or Mars (Jastrow, 1910, p. 222).[2] At some point, the group of wondering stars was given a single descriptive classification; indeed our word *planet* simply derives from the Greek for *wanderer*. It was thought that the stars and planets were composed of the same material, and differed only in their fixity and in the wandering stars' proximity to the earth.

What is a Planet?

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[1] It is worth noting that the planets are not mentioned in the Hebrew Bible (Rosen, 1965, p. 40).

[2] For reasons lost in time, I became enamored with the etymology of the planet Jupiter. As we know now, it is the largest of the planets. I had assumed that this was ancient knowledge, which caused them to name the planet after *deus pater*, the father of the gods. As it turns out, this was not ancient knowledge (van Helden, 1985). The Romans inherited their astronomical knowledge from the Greeks who inherited their knowledge from the Babylonians, and the identification of Jupiter with Marduck, who was the chief god in the Babylonia pantheon, is artificial and arbitrary (Jastrow, 1910, p. 217). [More notes on this: In ancient times, it was thought that Venus was the largest star (Condos, p. 167). Historically, one of the greatest astronomical insights was separating apparent size from brightness. What gave rise to the concept of absolute distance. But, see Heath, 1991, p. 129. Plato does not give a reason for the naming of Jupiter (Heath, 1991, p. 62). Perhaps it was because of its brightness (Heath, p. 1991, p. 130).]

As we now know, the celestial world is filled with an array of objects, moons around other planets, new planets, and an entire swarm of rocky bodies concentrated in the gap between Mars and Jupiter. Each of these objects had to be discovered and classified. These discoveries and classifications are the theme of the rest of the paper.

Historically, common sense and philosophical argument persuaded most people that the earth was the center of the universe. From this vantage point, the astronomer Ptolemy provided a view of the cosmos that allowed astronomers to predict the planets' locations. Though the mathematics is beyond the scope of this paper, there were a number of assumptions in Ptolemy's model that served to underpin his cosmology: a stationary earth that was the focus of all the circular motion surrounding it.

Although his model ruled for millennia, within one century, it would crumble when Copernicus, Galileo, and Kepler fundamentally re-conceptualized the nature of stars and planets. In particular, these shifts would fundamentally alter the meaning of the word *planet*. In so doing, these shifts also altered humanities' view of itself in the cosmos.

As we have said, the Ptolemaic system has ruled for over a millennium. Though usually successful, it had become a model of *ad hoc* Rube Goldberguan complexity. Partially in an effort to simplify astronomical predictions, and remove some of this complexity, the astronomer Copernicus moved the earth from the center of the cosmos and made it just another planet orbiting the sun. This choice was not arbitrary. Copernicus, and then Kepler, showed that the Earth appeared to move like other planets. In one of the most important sentences in the history of astronomy, Copernicus wrote,

> Therefore, since nothing inhibits the mobility of the Earth, I think we should now see whether more than one movement belongs to it, so that it can be regarded as one of the wandering stars (Copernicus, pp. 520–521).

While Copernicus laid the groundwork, Kepler showed that the motion and orbit of earth was like that of the other planets (Ferguson, 2002, p. 307–308). In other words, at this point the word *planet* started to change its meaning from "a light that wanders in the sky" to "an object that wanders when viewed from the sun."

In a series of researches, Galileo demolished three other edifications of the Ptolemaic view: He showed that the moon was similar to the earth, then that Venus was similar to the moon—so, by transitivity, Venus and the other planets were similar to the earth. Finally, he showed that the earth was not the only center of motion in the cosmos. First, Galileo's observations of the moon showed that it was rugged like the earth. He saw that the dividing line between light and dark was not smooth, and he noticed that there were things on the moon that acted just like mountains on the earth (e.g., were lighter on the side to the sun and darker to the other side, etc). The similarity of one celestial body to the earth supported the idea that the each might be a celestial body on its own (Hirshfeld, 2001, p. 122).

If the first shift was making the earth like one of the celestial bodies, the second was making one of the celestial bodies like the moon. Galileo observed that Venus goes through a full set of phases. According to Ptolemy's model, Venus should not show the full set of phases. So, what Galileo discovered was not that Venus had phases but that it had an entire cycle of phases. As he said in an anagram to Kepler, "Cynthiae figuras aemulatur mater amorum" (the mother of loves [Venus] emulates the figures of Cynthia [the Moon]) (van Helden, 1995). Fundamentally, this showed that at least one of the planets was similar to the moon in that it shown by reflected light.

Based on their telescopic differences, in that the planets looked spherical but stars as points of light, Galileo suggested that the planets were different in kind from the stars (Drake, 1957, pp. 45ff; van Helden, 1985, p. 67). Though Galileo provided the data, it was Kepler who finally realized this was the essential difference between the fixed and the wandering stars: stars twinkled and planets did not. As he goes on to say,

> What other conclusion can we draw from this difference, Galileo, that that the fixed stars generate their light from within, whereas the planets, being opaque, are illuminated from without; that is, to use Bruno's terms, the former are suns, the latter, moons or earths? (Rosen, 1965, p. 34).

So, by conclusion: the plants as a group had light different from the stars, and at least one of the planets was like the moon in that is shown by reflected light. By implication, perhaps all the planets were like the moon in that they all shown by reflected light. If this were so, the division between the celestial and the terrestrial starts breaking down.

Third, when Galileo observed Jupiter, he observed that there were points of light—which he called planets—orbiting it. Indeed, all through *Siderus Nuncius*, his report on the objects, Galileo calls the new moons *planets*; it was Kepler who surmised that they were moons (Galilei, 1989, p. 94). This fact showed that the earth was not the only center of motion in the universe.

At this point, we are left with a new model of the cosmos, with the sun at the center, and six planets orbiting the sun. In this model, to reiterate, the definition of planet shifted so that the earth was just one of the planets. This model provided a new sense of stability until it was overturned by new objects that had not been expected in these classical models.

Uranus

On the evening of 13 March 1781, William Herschel was scanning the skies with his 7-foot telescope looking for double stars. While in the neighborhood of H Gemini, he noticed a star which was visibly larger than other stars (Grosser, 1979; Herschel, 1781; Standage, 2000). At first, he thought he had discovered a new comet.[3] For a few months after its discovery, several astronomers tried to fit the observations to a parabolic, cometary, orbit. Other astronomers, observing Herschel's new object, remarked that it

[3] When Herschel first spotted the object, he wrote in his journal that he had found a "curious either nebulous star or perhaps a comet" (quoted in Lubbock, 1933, p. 77). Four days later, when he saw that the object had moved, showing that it was not a nebulae, he wrote in his journal that he "looked for the Comet or Nebulous Star" (quoted in Bennett, 1982, p. 49; note the shift in the order of terms). One month later, in his first public report of his discovery, he wrote that when he saw the object he "suspected it to be a comet," with no mention of the nebulae (Herschel, 1781/1982, p. 9). When later observations determined that it was actually a planet, Herschel's memory again changed. In an account of his life written years later, he wrote, "I perceived its visible planetary disk as soon as I looked at it" (quoted in Lubbuck, 1933, p. 79). It is apparent that as time passed, Herschel moved from mentioning his initial ambiguity about whether the object was a nebulae or comet to asserting his immediate certainty that it was a planet. What is probably true is as he reports later. "The first moment I directed my telescope to the New Star, I saw with the power of 227 that it differed sufficiently from other celestial bodies; and when I put on the higher powers of 460 and 932 was quite convinced that it was not a fixed star" (Hoyt, 1980, p. 21). Clearly, this is an interesting example for the psychology of memory.

looked nothing like any comet that they had ever seen. For example, three days after Herschel's paper describing his new object was read, Charles Messier wrote to Herschel that he and Maskelyne had observed his object and found it "of a very singular character, having no atmosphere, resembling a little planet . . ." (Messier, quoted in Grosser, 1979, p. 20). A little later, Messier says, "I am constantly astonished at this comet, which has none of the distinctive characteristics of comets (p. 20). Later that summer, Anders Lexell summed up the observed characteristics of Herschel's object and decided that it was a new planet, and on this basis computed an orbit for it (Grosser, 1979. p. 21). Shortly after Lexell's work, it was widely accepted that Herschel had discovered the first planet in recorded history: Uranus.

Although Lexell had fit a planetary orbit to Uranus, Uranus was soon off its predicted position (for a more complete story, see Gould, 1850). In 1783, Laplace and Méchain published new orbital elements for Uranus based on observations from the previous two years. Because of the paucity of the data, and the long time that it would take Uranus to complete one orbit around the sun, these orbital calculations were not very precise. In 1784, Johann Bode realized one way around these problems. Because Uranus is a fairly bright object, actually even barely visible to the naked eye, and because its orbit is along the ecliptic, Bode predicted that Uranus would have been seen by other astronomers prior to its discovery and mislabeled as a star (Forbes, 1982). So, Bode began searching through old star catalogues looking for objects labeled stars near where Uranus would have been. By 1821, Bode and other astronomers had discovered seventeen pre-discovery observations of Uranus (Forbes, 1982). (Recent investigations have revealed no fewer than 22 pre-discovery observations of Uranus, from 1690–1771.) We can feel especially sorry for Pierre Lemonnier, who recorded Uranus *twelve* times before it was discovered (Hoyt, 1980, p. 33).

In 1821, Bouvard attempted to reconcile these historic observations with modern ones and compute Uranus' orbital elements. He quickly realized that no orbit would fit the available data. So, after all the effort spent to find the historical observations, Bouvard decided to discard them and compute orbital elements based solely on the modern observations of the previous forty years. Even after discarding the ancient observations, Uranus could still not be made to fit an elliptical orbit and Bouvard's tables left a few minutes of arc discrepancy in Uranus' orbit. Even allowing for these discrepancies, Uranus was soon off its new computed orbit.

Because of the precision which mathematical astronomy had reached, the situation was growing rather desperate and various proposals were put forth to explain Uranus' behavior. Two of the most popular ideas were that Newton's laws were not exact out to that distance (this is, in other words, a reminiscence of the view that the earth is in some special place in the cosmos) or that there was a planet exterior to Uranus (Forbes, 1982). Because it would both explain Uranus' behavior, and also Nicolai's observations that Halley's comet was being perturbed past Uranus, many mathematicians opted for the later solution and took up the challenge to find where this planet would be located (Gould, 1850; Grosser, 1979; Morando, 1995; Standage, 2000). Of these, two would ultimately make clear predictions.

The Discovery of Neptune

Working independently, John Adams and Urbain LeVerrier tried to locate the planet they believed was pulling on Uranus. In the history of astronomy, this tale is one of those that bears repeated contemplation. As we consider the story, we will confront first-hand many of the difficulties in any predictive science. These include one's premises, one's prediction, and assigning credit.

While we need not go into all the math (but see Smart, 1947), there were several characteristics of the unseen planet that both Adams and LeVerrier had to determine in order to localize the planet in the sky. The most important characteristics were the planet's average distance from the sun (i.e., its semimajor axis), its eccentricity, the orientation of its ellipse, its actual position, and its mass (Smart, 1947). Quite clearly, one could have a large planet that was further from the sun or a smaller planet closer to the sun exert the same influence on Uranus. After one had determined these elements, one could then attempt to visually locate the object in the sky.

Though I do not want to detail the mathematics, there is one point that deserves mention. In his attack on the problem, LeVerrier did not begin by assuming there was a planet exterior to Uranus (as Adams did; Jones, 1947); rather, he first demonstrated that the motions of Uranus could not be accounted for except by an unknown planet (Gould, 1850). It was only after eliminating these as other possibilities that he then turned to the orbital characteristics of this planet.

In order to simplify at least one of the unknowns, both Adams and LeVerrier initially referred to a peculiar relationship among the then known planets known as Bode's law.[4] To understand the law, and to make the math simpler, let us set the earth's distance from the sun as 10. We can then explain each planet's distance from the sun in a very simple relationship. Mercury is closest, and its distance is 4 on this scale. For each subsequent planet, we have the following relationship: $4 + 3(2^n)$. So, Venus would be $4 + 3(2^0) = 7$ units from the sun. This fairly closely matches its actual relative distance. As one can see from table 1, the fit is actually fairly close for the planets out to Uranus. This fit for Uranus, unknown at the time the "law" was proposed, was considered confirmation of the law. Because Uranus' fit to the law was so close, several astronomers predicted that there must be an unseen body in the gap between Mars and Jupiter. After several false starts, on 1 January 1801, Giuseppe Piazzi found the first such object. As with Herschel, Piazzi thought he had found a comet (though privately thought he had found a planet; Smith, 1982). In due time, the object's lack of a planetary disk and the discovery of other objects in the same orbit as Ceres, led Hershel to realize that the cosmos contained a new type of object, which he termed "asteroids." Thus, we say that Piazzi discovered the first asteroid: Ceres.[5] Ceres was apparently another success for Bode's law, as Bode's law predicted a body a 2.8 AU and Ceres is at 2.77 AU (Hoskin, 1995; Hoyle, 1962, p. 168).

On any account, Bode's law would have had Adams and LeVerrier's unseen object 38.8 times further from the sun than the earth is.

With this value at least tentatively accepted, both Adams and LeVerrier could then attempt to determine the mass of the planet that would account for Uranus' motions. After this, one could specify where in the sky a planet of that size would have to be to have its effects. In theory, one would then merely have to point a telescope to the predicted location and confirm or refute the prediction.

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[4] Relevant in this context regarding credit, Bode did not discover Bode's law, but rather Johann Titius did (Jaki, 1972).

[5] As a further reason to reject rationalistic philosophies, at this time Hegel rejected Ceres as a planet because he had proved that there could only be seven planets (Grosser, 1979, p. 31).

At this point, before we consider the outcome of this search, let us consider to specific questions. First, just what did Adams and LeVerrier predict? Though we must make allowances for their context of knowledge, especially considering what they could and could not predict, we need to make our prediction as specific as the context allows for easier verification and falsification. We need to consider the context of the prediction, that is, what magnitude are we talking about. We would not expect an astronomer to predict the position of a planet within a few centimeters, but we could expect the same from a microbiologist. So, for example, we could expect Adams and LeVerrier to predict the planet's location to a relevant specificity but we would not demand that they predict its color. In this view, Adams and LeVerrier predicted a particular type of object and to be valid the object they found must match those characteristics; at a bare minimum, we would say they predicted the semimajor axis, the mass, and the location of the object in the sky at a certain point. Further, these values give rise to different orbital characteristics of their unseen object. Following Kepler's laws, an object with a different semimajor axis will have a different period.

Second, before we know the outcome, let us specify what counts as a confirmed prediction. This should be considered ahead of time because once the reports are in we are very good at allowing what we want to be the case to have been predicted to be the case. So, at this point, before we consider the outcome, we can say that a prediction must be specific, contextually relevant attributes of the entity and be falsifiable. Let us consider an example, if I say that "Jack is dating Jill," I am saying that Jack is dating someone *and* that someone is Jill. If it turns out that Jack is dating Sue, I would be wrong. In the same way, we cannot simply say that Adams and LeVerrier predicted an object and award them credit if one happens to be found—they predicted a specific object.

Third, what counts as having made a creditable prediction? I can assert what I wish in the privacy of my own heart or to my private journal. Even if I could document my private prediction, this seems limited. To count as a creditable prediction, one should stick their reputation on the prediction. In this sense, the prediction should be public. While the prediction could be public in many different ways, to count it should be public in the ways defined by a particular society. So, mentioning a new finding in my personal web log would not count.

At this point, before we know the outcome, let us consider the relative predictions of Adams and LeVerrier. LeVerrier predicted the existence of a planet exterior to Neptune, and published his predictions in the relevant journals of his day. In other words, LeVerrier risked his reputation on his predictions.

In contrast, Adams did not publish his predictions. Actually, in order to decide on whether Adams would deserve any credit, we have to consider his actions in a bit more detail. This much is certain: Adams began work on the problem on the unseen planet before LeVerrier did and prior to any potential discovery. Second, Adams tried to persuade the relevant authorities to look for his unseen planet, but they, for the most part, drug their feet believing the problem too hard or the predicted planet too dim (Smith, 1989). Third, though he did conceal his data from the world at large in order to secure greater glory for England (particularly Cambridge; Smith, 1989), he did attempt to present his data at the British Association for the Advancement of Science. As it turns out, however, the relevant section finished their conference earlier than planned.

Though Adams did attempt to present his data to the relevant astronomers, he was put off by what he felt was an irrelevant question from the astronomer royal, George Airy. Unknown to Adams, Airy had long been bothered by estimates of Uranus' average distance from the sun[6]. When Adams approached Airy with a specific prediction and asked for his assistance, Airy expressed interest and asked him whether his data would also remove difficulties in the Uranus' distance from the sun. At this point, Adams waited a year to respond, mainly because he felt that the question was trivial and he felt that resolving the difficulties in the motion of Uranus' longitude would explain any difficulties in Uranus' distance from the sun (Jones, 1947).[7] Later, when Airy asked LeVerrier the same question, he sent him a prompt response.[8]

Now, we can return to our story. Independently, as we have seen, Adams and LeVerrier worked out predictions on the location of Neptune. After receiving LeVerrier's paper, Airy finally directed a telescope to look for the unseen planet[9]. He instructed the astronomer Challis to search an area roughly the area equivalent to Orion, Gemini, and Cancer; it is also roughly the area of Orion and Taurus combined. According to Grosser (1976), there were roughly 3000 stars down to 11th magnitude in the area that Challis was trying to map.

Meanwhile, in France, LeVerrier's papers caused considerable interest, just not among those who manned the telescopes. LeVerrier could not get any of his countrymen to turn

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[6] Though he is often ridiculed for this seemingly trivial detail, George Airy's autobiography confirms his long standing interest in this question. In the notes for 1838, he writes, "The perturbations of Uranus were now attracting attention. I had some correspondence on this subject with Dr. Hussey in 1834, and in 1837 with Eugene Bouvard. On Feb. 24th of 1838, I wrote to Schumacher regarding the error in the tabular radius-vector of Uranus, which my mode of reducing the observations enabled me to see" (1896, pp. 133–134). In 1845, the year before Neptune's discovery, Airy wrote, "But in this year began a more remarkable planetary discussion. On Sept. 22th Challis wrote me to say that Mr Adams would leave with me his results on the explanation of the irregularities of Uranus by the action of an exterior planet. In October Adams called, in my absence. On Nov. 5th I wrote to him, enquiring whether his theory explained the irregularity of radius-vector (as well as that of longitude). I waited for an answer, but received none" (pp. 168–169). Further, much has been made of Adams' abortive attempts to visit Airy. Without rehashing old debates, it is worth noting that Adams (an unknown mathematician) tried to see Airy (the astronomer royal) in person without an appointment during an extremely busy time for Airy (e.g., his wife was about to give birth, there were legal cases going on, he was traveling on commissions) and yet Airy still wrote to Adams expressing interest in hearing his response by letter.

[7] Though Adams may not have known, Airy also did not believe that it was possible to mathematically predict a planet (Airy, 1846), had his doubts about Newton's laws, and he did not consider his office to be in the business of finding planets (Chapman, 1988; Jones, 1947). Further, Airy disagreed with Adams' assertion that explaining the problems in longitude would explain problems with the radius vector (Jones, 1947, p. 19).

[8] In this context, it is worth again quoting from Airy's autobiography. In an entry for 1846, Airy wrote, "The engrossing subject of this year was the discovery of Neptune. As I have said (1845) I obtained no letter from Adams to a letter of enquiry. Beginning with June 26th of 1846 I had correspondence of a satisfactory character with Le Verrier, who had taken up the subject of the disturbance of Uranus, and arrived at conclusions not very different from those of Adams. I wrote from Ely on July 9th to Challis, begging him, as in possession of the largest telescope in England, to sweep for the planet, and suggested a plan. I received information of its recognition by Galle, when I was visiting Hansen at Gotha. For further official history, see my communications to the Royal Astronomical Society, and for private history see the papers in the Royal Observatory. I was abused most savagely by both English and French" (p. 181).

[9] If one wonders why it took this second paper, the answer is that Airy thought that Adams' prediction was based on certain assumed elements and that "the investigation could scarcely be considered satisfactory while based on anything so arbitrary" (Airy, 1846, p. 137).

their telescopes to the point in the sky that he had predicted, mainly because they did not believe that LeVerrier's results necessarily meant the physical existence of just such a body (Gould, 1850). In the words of Galle, who we will consider in a moment, they did not turn their telescopes toward that area because "while much labor was certain, success appeared doubtful" (quoted in Gould, 1850, p. 19). Finally, under the pretext of thanking him for a copy of a paper, he wrote to Johann Galle in Berlin and asked him to look in that area of sky. Galle obtained permission to do so, and then he and one of his assistants, Heinrich d'Arrest, pulled out a newly created star map of the area and began their search. While looking through the scope, Galle would call out objects and d'Arrest would check them off the chart. Shortly before midnight on 23 September 1846, Galle described a faint object and d'Arrest called out those immortal words, "That star is not on the map." They had found LeVerrier's planet around half a degree (roughly equivalent to the diameter of the moon) from where LeVerrier predicted it would be and less than a degree and a half from where Adams predicted it would be (see Figure 1).

Shortly after its discovery, it became clear that the planet predicted by LeVerrier and Adams differed in some fundamental ways from Neptune (see Table 2). Indeed, one could almost say that other than happening to be in the same position of the sky at that particular point in the time, the real Neptune was unlike the object predicted by LeVerrier and Adams. We will return to this issue shortly.

Pluto

After the discovery of Neptune, early reports suggested that it could not fully account for the irregularities in Uranus' orbit. Just as with Adams and LeVerrier, several astronomers and mathematicians attempted to compute orbits for an unseen planet tugging on both Uranus and Neptune. Though there were several astronomers who made such predictions, we need only concern ourselves with one: Percival Lowell.

To the extent that he is remembered, most people associate Lowell with his theories regarding sentient life on the planet Mars. Quite apart from these theories, however, Lowell was heavily involved in predicting and funding research on the possibility of a planet exterior to Neptune (Hoyt, 1980).

In his efforts to predict the existence of a planet exterior to Neptune, dubbed Planet X, Lowell concentrated on the residuals of Uranus and Neptune's orbit, and on the locations of the aphelions of comets. In the course of his work, Lowell made numerous predictions about the location of this planet, its distance from the sun, and inclination. In one set of predictions, Lowell localized his unseen planet in nearly 120º of the sky (Hoyt, 1980, p. 137)! In one of his major published works, Lowell gave two equally strong predictions for this planet's orbital characteristics that differed from one another by 180º (Russell, 1930). It has been argued that one of these predictions, his planet X_1 resembles Pluto (presented in Table 3). Though he attempted to predict its existence mathematically, in the end Lowell thought that the best hope for finding his planet "lay in the systematic photography of those regions of the sky generally indicated by his many solutions" (Hoyt, 1980, p. 124). In the end, this is how the object associated with Lowell would be discovered.

After his death, and a decade hiatus of the first world war, Lowell's workers at his observatory set to work again on the problem of Planet X. As suggested by Lowell, they decided to take an observing approach to its discovery. In the course of this tedious work, they hired Clyde Tombaugh to serve as an assistant. His job was to take several pictures of areas of the sky at different times and then to compare these in a "blink comparator." In essence, he compared two images of the same region of sky, first looking at one and then the other to see if an object moved on the pictures. The tediousness of this work was immense, and Tombaugh deserves due credit for his refinement of the technique, the skill and perseverance he brought to this task, and the myriad of objects that he discovered.

Just over a year after he began his work, on 18 February 1930 Tombaugh was examining plates and noticed that one object appeared to move in the comparator (Tombaugh, 1960). He had found, it was thought, the object that Lowell predicted.

As with Neptune, when describing a planet, one must list certain critical facts about that planet and its orbit. If we compare Lowell's predictions with Pluto, we find that there is very little agreement (see Table 3). Many individuals have argued that Pluto was found near one of Lowell's predictions and have argued that such a finding cannot be coincidence. Let us remember, however, that Lowell made two separate final predictions of the unseen planet. Pluto was found nearly 6 degrees away from one of the predicted locations.[10] Let us then allow that this is Lowell's presumed margin of error, though there is no basis for this. We then have Lowell predicting the existence of an unseen planet and allowing himself nearly 24 degrees (2 predictions times 6 degrees on either side of his prediction) of leeway, amounting to 6.4% of the ecliptic that he can claim as accurate. Actually, this understates the case. Lowell also thought that Pluto's inclination was plus or minus 10 degrees. Actually, Lowell also thought the planet would be found south of the ecliptic, while it was found far north. Its true inclination was 17.1 degrees—over 70% greater than his most extreme prediction. Repeatedly Lowell urged his workers to photograph south of the ecliptic; only when the planet wasn't found there did he then urge them to photograph to the north (Hoyt, 1980, p. 125). Most importantly, however, Pluto's mass is orders of magnitude less than Lowell predicted (Rawlins, 1960)[11]. Since its discovery, Pluto's mass has been constantly revised downward, until we now realize that Pluto's mass is one-fifth that of the earth's moon, and its size is less than a half dozen moons in the solar system (the moon, Io, Ganymede, Callisto, Titan, and Triton). Further, its moon Charon's radius is 52% of Pluto's and its mass is 14%; this compares to 27% and 1.2% for the same earth-moon comparisons. Charon's mass is so great relative to Pluto that their barycenter, their common center of motion, is actually exterior to the two bodies (Lodders & Fegley, 1998, p. 238). Pluto is unusual in a number of its other characteristics, especially the inclination of its orbit (17.2º), its eccentricity, and the relative size of its moon to itself. For example, because of its eccentric orbit, it crosses Neptune's orbit. Ironically, however, it passes closer to Uranus (12 AU) than it ever passes to Neptune (17 AU) (Lellouch, 2001). The origin of Pluto's orbit causes great difficulties, and it seems to suggest a different origin than those of the other planets (Peale, 1993; Malhotra, 1993).

In the end, we have an object predicted to explain discrepancies that did not exist (Littmann, 1989), unpredictable by these alleged discrepancies, and too small to explain the purported discrepancies (Russell, 1930, p. 22; Tyson, 2003). In short, Pluto is not the body predicted by Lowell. In the end, we must agree with others who argue that "Tombaugh's discovery of Pluto in 1930 was the result of the comprehensiveness of the

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[10] For the record, LeVerrier only allowed himself a 5º margin of error (Pierce, 1847, p. 61).

[11] Russell (1930) already shows some equivocation, even when it was thought that Pluto's mass was 5 to 6 times earth's mass.

search rather than the predictions from planetary dynamics" (quoted in Hoyt, 1980, p. 245).

In the end, just what is Pluto? While we consider the nature of planethood in the discussion section, we should mention here that there are a number of bodies out in the region of Pluto. For example, one object named Quaoar has half the diameter of Pluto and crosses Pluto's orbit (Hecht, 2002).

The Nature of Discovery

To be valid, predictions must be substantiated and verifiable. The justification for this follows from metaphysics and epistemology. When we assert a positive claim, we are *asserting* the existence of *something*. Because we are asserting, we must provide the justification for this claim. Second, because we are asserting the existence of something, and because entities have a nature determined by their characteristics, we must specify the characteristics of our predicted object. As part of this, we must have a way to validate the claim.

The importance of these principles becomes evident as we consider the history of astronomy. First, there is hardly a single discovery that hasn't been claimed to have been discovered before. Second, individuals often make claims that later turn out to be correct but without justification.

Let us for a moment consider the planet Mars, circled by the small satellites Phobos and Demos. Though these satellites were not discovered until 1877 by Asaph Hall, their existence had been asserted on several previous occasions (Sheehan, 1996). The first assertion was really by accident. Galileo had sent Kepler and others an anagram announcing the odd shape of the planet Saturn. He had sent the following, "smaismrmilmepoetaleumibunenugttauiras", which Kepler incorrectly decoded as "Hail, twin companionship, children of Mars" (Sheehan, 1996, p. 17). Later, Jonathan Swift, possibly influenced by this episode, writes that Gulliver, while visiting the inhabitants of Laputa, learns

> They have likewise discovered two lesser Stars, or Satellites, which revolve about Mars; whereof the innermost is distant from the Center of the primary planet exactly three of his diameters, and the outermost five; and the former revolves in the space of ten hours, and the latter in twenty-one and an half, so that the squares of their periodical times are very near in the same proportion with the cubes of their distances from the center of Mars; which evidently shews them to be governed by the same Law of Gravitation that influences the other heavenly bodies.

Germane to our story, Herschel thought that Uranus had rings and claimed to have seen them (Hoyt, 1980, p. 22). As it turns out, Uranus does have rings, though one cannot see these rings except under unusual conditions, and it is unlikely that Herschel actually saw Uranian rings. Should he get credit for their discovery?

On the other hand, many times in the history of astronomy objects have been seen prior to their official discovery. Interestingly, the objects of two of the most historically important astronomical discoveries—the moons of Jupiter and the planet Uranus—lie just at the limit of naked eye visibility. As it turns out, there are claimants to having seen Jupiter's moons prior to the official discovery; though there are no naked eye claimants to observations of Uranus, we have seen it was telescopically observed prior to its discovery. Actually, as we shall see, every trans-Saturnine planet was spotted prior to its official discovery.

First, let us consider the largest moons of Jupiter. In the official account, Galileo turned his telescope toward Jupiter and observed the Galilean moons. As we have already seen, the real story is a bit more nuanced; Galileo consistently referred to them as planets, not satellites. There is one more rub to the story, however, a rub which addresses what it means to discover an object. In Galileo's time, Simon Mayr claimed to have seen Jupiter's moons before Galileo did. For his part, Galileo exposes Mayr's tricks of the calendar and demonstrated that he first saw the moons (Drake, 1957). In recent times, there has been an even older naked-eye claimant. As the moons of Jupiter lie at the limit of naked eye visibility, it might be possible to observe them under very favorable conditions (North, 1995). Indeed, it seems that they were observed prior to Galileo's discovery. The 4th century BCE Chinese astronomer, and regular observer of Jupiter, Gan De wrote,

> In the year of Chan yan . . . (Jupiter) at Zi . . . appeared in the morning in the beginning and disappeared in the evening at the end of this year. Jupiter was very large and bright, it looked like it had a small reddish (chi) star attached to it; this was called a "league" (Ze-zong, 1982, p. 665).

Based on an analysis of the passage, and a favorable viewing of Jupiter, Ze-zong was able to confirm that one could indeed see at least one of Jupiter's satellites with the naked eye, and that Gan De saw and reported his observation of Ganymede.

If one wanted to defend Galileo's priority, one could point out that Gan De did not demonstrate that the star revolved around Jupiter (cf., Hartmann, 1985), but by the same token one could point out that Galileo did not recognize the difference between planets and satellites.

Earlier we mentioned Galileo's anagram which was mistranslated by Kepler. After his discovery of the moons of Jupiter, Galileo noticed that Saturn appeared to be a triple planet (Levy & Wallach-Levy, 2001, p. 65). Because of the poor resolving power of Galileo's telescopes, however, he could not explain Saturn's appearance. To try to establish priority, he sent the anagram mentioned earlier, and anagram whose actual meaning is "I have observed the most distant planet in triple form." Though Galileo observed this irregularity, he is not credited with the discovery. It is Christian Huygens who gets credit for discovering that they were rings.

Finally, we can consider one other relevant Galilean discovery. When he was observing the Jupiter's moons, Galileo saw and drew Neptune (Drake & Kowal, 1980; Kowal & Drake, 1980). Not only did he observe Neptune, but he actually noted that it had moved with respect to a fixed star. Actually, not only had Galileo noticed the movement of Neptune prior to its discovery, so did Lalande (Harrison, 1994, p. 31). In other words, two individuals noticed the movement of Neptune prior to its discovery.

Finally, we can return again to the predictions that led to the discoveries of Neptune and Pluto. What, exactly, was Adams and LeVerrier's prediction? Was it simply that a planet exists exterior to Uranus and was causing the orbital irregularities? In that, they were correct. But, in the next step, predicting the orbital properties of the planet, they was wrong about every single fact—except where the planet was in the sky at that particular time.[12] In a similar way, as we have seen, Lowell was wrong about nearly every characteristic of Pluto, and was only correct about its location if we consider one of his many predictions and make great allowances.

Discussion

At this point, we can finally consider the many issues raised by the discoveries of the moons of Jupiter, Uranus, Neptune, and Pluto. In particular, we can concentrate on the nature of science, the nature of credit, and the nature of a planet (and whether Pluto should be considered one).

These discoveries fundamentally changed our view of the universe. They show how, in a clear way, accepted beliefs do not change simply because one or two exceptions were found, but rather there had to be a complete shift in the way of viewing the world (somewhat akin to that described by Kuhn, 1970). The essential reason for this is that any belief has a number of other implications. With any intelligent individual, we find that their ideas are to a greater or lesser degree integrated with their other ideas. Thus, when they discover that one is false, they do not immediately alter their beliefs. Typically, the older one is the more of the interconnections one has formed.

Earlier we indicated certain qualities of creditable predictions. If we compare Adams and LeVerrier's predictions with the actual planet, however, we face a number of problems. Since its discovery, a number of astronomers have agreed with Lyttleton when he writes, "There is considerable doubt as to the extent to which it was a logical consequence of their mathematical calculations" (1968, 216–217). Actually, one might be tempted to make a stronger negative claim regarding Neptune. We could, with Benjamin Peirce, conclude that

> Without any hypothesis in regard to the character of the orbit . . . the planet Neptune is not the planet to which geometrical analysis has directed the telescope; that its orbit is not contained within the limits of space which have been explored by geometers searching for the source of the disturbances of Uranus; and that its discovery by Galle must be regarded as a happy accident (Pierce, 1847, p. 65).

On the whole, Neptune is not the planet predicted by Adams or LeVerrier. It is far smaller and closer than their predicted planet. Further, as the average distance from the sun influences the orbit, Neptune also has a completely different orbit than predicted. Indeed, if Galle and d'Arrest had not looked when they did it is possible that Neptune would not have been discovered for many more years. These problems are only exponentially compounded when we consider Lowell's predictions as compared to Pluto's characteristics. As a consequence, I will no longer consider Pluto as in any way predicted by Lowell's mathematical labors.

Let us grant for the moment, however, that either Adams or LeVerrier deserve credit for prediction of Neptune. Should they receive equal credit? After Neptune's discovery, this was a hotly debated question, leading to some joint awards and some to LeVerrier alone. With the remove of history, I think that they do not deserve equal credit. It is not

[12] It should be pointed out that Peirce showed that there were actually several solutions, all different from one another, that would have also solve the equations of Adams and LeVerrier (Gould, 1850; Pierce, 1847, p. 144ff). Gould is actually more explicit later. Once we consider solutions that reduce the errors in Neptune's orbital characteristics, we get two solutions, "One is included within the theory and limits of Leverrier, and corresponds with Adams' solution; the other is the orbit of Neptune" (1850, p. 55).

that I think that LeVerrier is a better mathematician than Adams, or a more original thinker. The point is this: LeVerrier, not Adams, risked his reputation on his researches. Further, LeVerrier's work, not Adams', was instrumental in Neptune's discovery. Even when British astronomers, such as Challis, searched for Neptune they used LeVerrier's method (essentially looking for a disk) and not Adams' (Airy, 1846; Jones, 1947).

It is possible, in the privacy of one's own heart, to hold whatever potentially absurd or insightful views one wishes without fear of reprisal or credit. If recognition is a value, and values are those which one first acts to gain, then we can only accord the value of recognition on those who publicly acted. In this vein, John Adams' story is doubly sad, but not deserving in credit. He almost publicly predicted the existence of a planet whose characteristics do not match those he predicted. In this context, even Adams asserted, "There is no doubt that his researchers were first published to the world, and led to the actual discovery of the planet by Dr. Galle, so that the facts stated above cannot detract, in the slightest degree, from the credit due M. Le Verrier" (Adams, 1847, p. 150)[13]. Furthermore, Airy has written that he did not feel that it was his obligation to publish Adams' results, but had Adams answered his question about Uranus' distance from the sun, he would have at once "exerted all the influence which I might possess . . . to procure the publication of Mr. Adams' theory" (Airy, quoted in Smart, 1947, p. 56). Finally, we must agree with Airy when he writes, "It would not be just to institute a comparison between papers which at this time exist only in manuscript, and papers which have been printed by their authors" (1846, p. 144).

To illustrate the importance of publishing, we must not only consider an individual's potential or actual successes, but also their failures. After his success with Neptune, LeVerrier went on to try to explain the peculiarities of Mercury's orbit. As with Uranus, LeVerrier believed that the difficulties could be resolved by an unseen planet orbiting interior to Mercury (Hanson, 1962). Not only did he predict such a planet, but believed that it had been spotted (Sheehan & Dobbins, 1998), publishing both his prediction and the believed sighting. As there is no such planet, it is clear that LeVerrier would bear the failure for such public prediction.

In addition to the risk of one's reputation, a published prediction also establishes a priority for any rewards that come from a verified prediction. This establishment of priority is crucial. Indeed this may be the main function of a scientific paper (Merton, 1957; Price, 1963). As Thomas Edison once commented in a different context, "No sooner does a fellow succeed in making a good thing, than some other fellows pop up and tell you they did it years ago" (quoted in Dyson & Uhlig, 2001, p. vii). In an analogous way, after discoveries it is quite common for someone to come on the scene and later claim they found the same thing first. Or, as Whitehead once said, "Everything of importance has been said before by somebody who did not discover it" (quoted in Ferris, 1988, p. 90). When they don't press their case, historians sometimes press it for them. Let us for a moment return to a quite pregnant image, that of Galileo showing Jupiter's moons along with the planet Neptune. Typically, Galileo is given credit for the discovery

[13] For what it is worth, as an undergraduate F. Hort (the future Greek New Testament scholar) heard Challis and Adams speak. In a letter to his father, he wrote, "Adams said that he gave Le Verrier full credit of the discovery, but, as a matter of calculation, he claimed himself the credit of prior independent conjecture" (quoted in Harrison, 1994, p. 35).

of the Galilean moons, but not Neptune—even though he saw, drew, and noticed that Neptune moved. However, he did not correctly identify what he saw.

It is irrelevant to argue that results have been conveyed in ways other than the scientific paper; it is only relevant that in the first half of the nineteenth century results were typically not conveyed in such a fashion. There are, to be sure, multiple routes of dissemination, but at this stage, letters about researches was not one of them.

Finally, we must return again to the question of "what is a planet?" As we have seen, the meaning of this word has changed tremendously since its origin. While it first referred to bright points of light that appeared to the naked eye to wander in our sky, to the earth as a planet and has come to include lights that do not wander to the naked eye. There are those that wish, however, to define planets by arbitrary features, such as having satellites, or meeting a certain size requirement.[14]

An entities' essence is not metaphysical, but rather epistemological. That is, we cannot expect to simply look out and have the world tell us what a planet is. On the other hand, concepts are not subjective either. Though he held that essences were metaphysical, Plato, in the Phaedrus (12:256e), introduced the valid principle "of dividing things into classes where the natural joints are, and not trying to break any part after the manner of a bad carver." Harry Binswanger (1989) expanded on this, saying,

> Nature is like a roast chicken. It's true that the roast chicken is not already cut up, and it doesn't already have dotted lines on it saying "cut here." So, god doesn't tell us where to cut the chicken. On the other hand, it doesn't mean that we can take the knife and just cut anywhere. If you want to avoid making a mess, you have to find the joints then cut it at the joints. So the joints are there, they're not labeled; they're not marked "cut here," and they're not physically separated. But there is a right place to divide phenomena and a wrong place.

As Rand says, concepts are properly formed considering the characteristics of an object while omitting the particular measurements (Rand, 1990).

As we consider the changing nature of the entities classified as planets, we are led to a few regularities. First, consistently planets are described as being "disk shaped" in the telescope. This, of course, means that they are spherical. Second, the lessons from Ceres and Pallas have taught us that planets exist as the major object in their orbit. Third, the moon defined plane of the ecliptic has served as the de facto path of planets (though I would be willing to concede that this is a non-essential). Finally, though the ancients thought the planets and the fixed stars both shined of their own light, the meaning of planet has come to mean "shines by reflected light."

As we have seen, Pluto does not fit these characteristics. Indeed, it most closely matches other objects that orbit exterior to the planet Neptune (Anonymous, 1999; Graham, 1999; Jewitt, Aussel, & Evans, 2001; Tegler & Romanishin, 2001). At least some of these objects, known as Kuiper belt objects, have orbits similar to Pluto and also have similar sizes (e.g., Varuna). Thus, by any objective epistemology, Pluto would be grouped with those objects and not with the other eight planets.

[14] For the moment, I wish to avoid the question about the lower limit of what can be considered a star (Anonymous, 1999), though with more discoveries of extra solar objects orbiting other stars this is a crucial issue.

We are thus led to this definition of planet: an object whose primary orbit is around the sun and at least spherical and more massive than any moon. By this criterion, Pluto is not a planet.

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Table 1

Predicted versus actual elements predicted from Bode’s law

Planet	Actual Orbital Radius	Predicted Radius
Mercury	4	$4 + 0 = 4$
Venus	7	$4 + 3(2^0) = 7$
Earth	10	$4 + 3(2^1) = 10$
Mars	15	$4 + 3(2^2) = 16$
Asteroids	28	$4 + 3(2^3) = 28$
Jupiter	52	$4 + 3(2^4) = 52$
Saturn	95	$4 + 3(2^5) = 100$
Uranus	192	$4 + 3(2^6) = 196$
Neptune	303	$4 + 3(2^7) = 388$

Table 2
Comparison of Predicted and Actual Orbital Characteristics of Neptune

Elements	Adams	LeVerrier	Actual
Mass (relative to sun)	1/6666	1/9300	1/19474
Semimajor Axis (a.u.)	37.25	36.15	30.06
Period	227.3	217.387	164.79
Eccentricity	.121	.108	.0086

Note. Data from Grosser (1962) and Kuhn (1998)

Comparison of Predicted and Actual Orbital Characteristics of Pluto

Elements	Lowell's X_1	Pluto
Semimajor axis (a.u.)	43	39.44
Eccentricity	.202	.25
Inclination	10º±	17.2º
Period	282	248.5
Longitude (1930.0)	102º.7	108º.5
Mass (Earth = 1)	6.6	.002

Note. Though it is not easy to indicate, Lowell also thought that his planet would show a clear disk 1" in diameter and have a visibility of 12–13. Suffice it to say, Pluto does not have either. Data from Hoyt (1980) and Kuhn (1998)

Figure 1
Adams and LeVerrier's predicted locations for Neptune on 23 September 1846 compared to Neptune's actual location.