submitted to ApJ Letters, March 16, 2004

Discovery of a candidate inner Oort cloud planetoid

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ABSTRACT

We report the discovery of the minor planet 2003 VB12 (popularly named Sedna), the most distant object ever seen in the solar system. Pre-discovery images from 2001, 2002, and 2003 have allowed us to refine the orbit sufficiently to conclude that 2003 VB12 is on a highly eccentric orbit which permanently resides well beyond the Kuiper belt with a semimajor axis of 480±40 AU and a perihelion of 76±4AU. Such an orbit is unexpected in our current understanding of the solar system, but could be the result of scattering by a yet-to-be-discovered planet, perturbation by an anomalously close stellar encounter, or formation of the solar system within a cluster of stars. In all of these cases a significant additional population is likely present, and in the two most likely cases 2003 VB12 is best considered a member of the inner Oort cloud, which then extends to much smaller semimajor axes than previously expected. Continued discovery and orbital characterization of objects in this inner Oort cloud will verify the genesis of this unexpected population.

1. Introduction

The planetary region of the solar system, defined as the region that includes nearly circular low inclination orbits, appears to end at a distance of about 50AU from the sun at the edge of the classical Kuiper belt (Allen et al. 2001, Trujillo and Brown 2001). Many high eccentricity bodies from the planetary region – comets and scattered Kuiper belt objects – cross this boundary, but all have perihelia well within the planetary region. Far beyond this edge lies the realm of comets, which are hypothesized to be stored at distances of $\sim 10^4$ AU in the Oort cloud. While many objects presumably reside in this Oort cloud indefinitely, perturbation by passing stars or galactic tides occasionally modifies the orbit of a small number of these Oort cloud objects, causing them to reenter the inner solar system where they are detected as dynamically new comets (Oort 1950, Duncan et al. 1987), allowing a dynamical glimpse into the distant region from which they came. Every known and expected object in the solar system has either a perihelion in the planetary region, an aphelion in the Oort cloud region, or both.

Since November 2001 we have been systematically surveying the sky in search of distant slowly moving objects using the Samuel Oschin 48-inch Schmidt Telescope at Palomar Observatory (Trujillo and Brown 2004) and the Palomar-Quest large-area CCD camera (Rabinowitz et al. 2003). This survey is designed to cover the majority of the sky visible from Palomar over the course of approximately 5 years and, when finished, it will be the largest survey for distant moving objects since that of Tombaugh (1961). The major goal of the survey is to discover rare large objects in the Kuiper belt which are missed in the smaller but deeper surveys which find the majority of the fainter Kuiper belt objects (i.e, Millis et al. 2001).

In the course of this survey we detected an object on 14 November 2003 which moved 4.6 arcseconds over the course of 3 images separated by a total of 3.1 hours (Figure 1). Over such short time periods, the motion of an object near opposition in the outer solar system is dominated by the parallax caused by the Earth's motion, so we can estimate that $R \approx 150/\Delta$, where R is the heliocentric distance of the object in AU and Δ is the speed in arcseconds per hour. From this estimate we can immediately conclude that the detected object is at a distance of $\sim$100AU, significantly beyond the 50 AU planetary region, and more distant than any object yet seen in the solar system. The object has been temporarily designated minor planet 2003 VB12.

Followup observations from the Tenagra IV telescope, the Keck Observatory, and the 1.3-m SMARTS telescope at Cerro Tololo between 20 November 2003 and 31 December 2003 [1] allow us to compute a preliminary orbit for the object using both the method of Bernstein and Khushalani (2000; hereafter BK2000), which is optimized for distant objects in the solar system, and a full least-squares method which makes no a priori assumptions

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[1] see http://cfa-www.harvard.edu/mpec/K04/K04E45.html for a table of astrometric positions.

about the orbit[2]. Both methods suggest a distant eccentric orbit with the object currently near perihelion, but derived values for the semimajor axis and eccentricity are very different, showing the limitations of fitting an orbit for a slowly moving object with such a small orbital arc. For such objects a time baseline of several years is generally required before an accurate orbit can be determined.

2. Pre-discovery images

For sufficiently bright objects, like the one discovered here, observations can frequently be found in archival data to extend the time baseline backwards in time. At each time that a new position in the past is found a new orbit is computed and earlier observations can then be sought.

The object should have been observed on 30 August and 29 September 2003 during drift-scans from the Palomar-QUEST survey Synoptic Sky Survey (Mahabal et al. 2003) also operating on the Samuel Oschin telescope at Palomar Observatory. From the November and December data we predict positions for 29 September with an error ellipse of only 1.2 by 0.8 arcseconds (though the two orbital determination methods disagree on precise orbital parameters, they both predict the same position within an arcseoncd). A single object of the correct magnitude appears on the Palomar-QUEST images within the error ellipse (Fig 2). A search of other available archival sources of images of this precise region of the sky, including our own survey data, additional Palomar-QUEST data taken on different nights, the Palomar Digitized Sky Survey images, and the NEAT Skymorph data base[3] finds no object that has ever appeared at this position at any other time. Below we will refer to such detections which are seen on one date only as “unique detections.” Unfortunately, individual images in the Palomar-QUEST survey are not taken long enough apart for us to determine if this object is moving or is instead a fixed source which was coincidentally bright only during the time of observation (a variable star, a supernova, etc.). We estimate the probability of an accidental unique detection within the error ellipse by examining the 5 by 5 arcminute region surrounding this object to see if additional unique detections randomly occur. We find no such unique detections in the surrounding region, thus the probability of such a unique detection randomly occurring within the error ellipse appears less than 10^{-4}. We conclude that this detection is indeed a pre-discovery image of 2003 VB12.

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[2] see http://www.projectpluto.com/find_orb.html

[3] see http://skyview.gsfc.nasa.gov/skymorph

Including this position in our orbit calculation shrinks the error ellipse for 30 August 2003 – another night of Palomar-QUEST observations – to less than an arcsecond. Examination of the 30 August 2003 Palomar-QUEST image and other archival images of the same location shows a unique detection at precisely the predicted location. Again, no other unique detection is found within a 5 by 5 arcminute surrounding box. We again conclude that this is our object with very low probability of coincidence.

From a four month baseline the orbital elements are still uncertain, but positions for the 2002 season can be predicted with reasonable accuracy. A search of the Skymorph database of NEAT observations shows that high-quality images were obtained surrounding the predicted location of our object from the Samuel Oschin telescope on the nights of 9 and 29 October 2002. The two orbital prediction methods described above predict positions separated by 8.5 arcseconds, though the BK2000 method suggests an error ellipse of semimajor axis only 4.2 arcseconds. This positional discrepancy is caused by an energy constraint in the BK2000 method which breaks degeneracies in short-arc orbits by preferring lower energy less eccentric orbits. The least-squares method, with no such constraint, finds a more eccentric orbit and therefore a slightly different position. We estimate an error ellipse for the least-squares method by a Monte Carlo method in which we add 0.3 arcsecond errors to our observations and recalculate an orbit and predicted position.

Figure 2 shows the 29 October 2002 NEAT data with both predictions and error ellipses. A single unique detection of the right magnitude appears within the full 5 by 5 arcminute field shown, and this detection is well within the error ellipse of the more eccentric least-squares orbital fit. The probability of the single unique detection randomly falling within either error ellipse is 5×10^{-4}. Including this detection in our fit breaks the orbital degeneracy, and now the BK2000 and least-squares method find essentially the same orbit and same errors. With the inclusion of the 29 October point, the error for 9 October 2002 shrinks to less than an arcsecond. Again, the only proper magnitude unique detection within a 5 by 5 arcminute area appears at precisely this location and we are confident that we have detected 2003 VB12.

Extension of the orbit to 2001 yields additional potential detections from the NEAT survey on 24 October and 26 September. The 24 October error ellipse is 2.1 by 0.7 arcseconds, and a unique detection of the correct magnitude appears within this small area. The data quality in 2001 is not as high as the previous data and this detection is near the limit of the images. Consequently the 5 by 5 arcminute surrounding area contains 3 additional unique detections of approximately the same magnitude. Nonetheless, the probability is only 1.5×10^{-3} of one of these random unique detections falling within our small error ellipse. The 26 September data contains a unique detection at precisely the right location, but also

3 other comparable unique detections within 5 arcminutes. The random probability is less than 10^{-3}. We conclude that both 2001 images indeed show our object.

Attempting to propagate the orbit to 2000 or earlier results in several potential detections but the data quality are sufficiently low that we deem the probability of coincidence too high to consider these. A special attempt was made to find the object in September 1991 Palomar Digitized Sky Survey images where the error ellipse is still only 26.7 by 1.1 arcseconds and while a unique detection can be found within the error ellipse, we find many potentially spurious unique detections at the same level and determine the probability for such a random detection to be as high as $\sim 3\%$, so we discount this candidate early detection as unreliable.

3. Orbital solution

The best fit BK200 orbit for the full set of 2001-2003 data yields a current heliocentric distance (r) of 90.32±0.02, a semimajor axis (a) of 480±40AU, an eccentricity e of 0.84±0.01, and an inclination i of 11.927. The object reaches perihelion at a distance of 76 AU on 22 September 2075±260 days. The RMS residuals to the best-fit error are 0.4 arcseconds with a maximum of 0.6 arcseconds, consistent with the measurement error of the positions of these objects. The full least-squares method gives results within these error bars.

The heliocentric distance of 90AU, consistent with the simple estimate from the night of discovery, is more distant than anything previously observed in the solar system. Many known Kuiper belt objects and comets travel on high eccentricity orbits out to that distance and beyond, so detection of a distant object is not inconsistent with our present understanding of the solar system. The distant perihelion is, however, unanticipated. The most distant perihelion distance of any well known solar system object is 46.6 AU for the Kuiper belt object 1999 CL119. To verify the robustness of the distant perihelion for 2003 VB12, we recomputed 200 orbits while randomly adding 0.8 arcsecond of noise (twice the RMS residuals) to each of the astrometric observations and find that the derived perihelion remains within the range 73 to 80 AU.

4. Origin

The orbit of this object is unlike any other known in the solar system. It resembles a scattered Kuiper belt object, but with a perihelion much higher than can be explained by scattering from any known planet. The only mechanism for placing the object into this orbit requires either perturbation by planets yet to be seen in the solar system or forces beyond the solar system.

4.1. Scattering by unseen planet

Scattered Kuiper belt objects acquire their high eccentricities through gravitational interaction the giant planets. Such scattering results in a random walk in energy and thus semi-major axis, but only a small change in perihelion distance. Scattering by Neptune is thought to be able to move an object's perihelion only out to distances of ∼36 AU. (Gladman et al. 2002), though more complicated interactions including migration can occasionally raise perihelia as high as ∼50AU (Gomes, 2004), sufficient to explain all of the known Kuiper belt objects. Our object could not be scattered into an orbit with a perihelion distance of 76 AU by any of the major planets. An alternative, however, is the existence of an undiscovered planet at a distance of ∼70 AU which scattered the object just as Neptune scatters the Kuiper belt objects. Our current survey has covered at least 80% of the area within 5 degrees of the ecliptic – where such a planet would be most expected – with no planetary detections (Brown and Truillo 2004). We therefore deem the existence of such a scattering planet unlikely, but not impossible.

Nonetheless, if such a planet does indeed exist – or did exist at one time – its signature will be unmistakable in the orbital parameters of all additional new objects detected in this region. All should have modest inclinations and perihelion similar to the 76AU perihelion found here.

4.2. Single stellar encounter

This unusual orbit resembles in many ways one expected for a comet in the Oort cloud. Oort cloud comets are thought to originate in the regular solar system where they suffered close encounter with giant planets which scatter them in to highly elliptical orbits. When these eccentric orbits take the comets sufficiently far from the sun, random gravitational perturbations from passing stars and from galactic tides modify the orbit, allowing the perihelion distance to wander and potentially become decoupled from the regular planetary system. Calculations including the current expected flux of stellar encounters and galactic tides show that a comet must reach a semimajor axis of $\sim 10^4$ before these external forces become important (Oort 1950, Fernandez 1997). Once comets obtain such a large semimajor axis the orbits become essentially thermalized, with mean eccentricities of 2/3 and isotropic inclinations. Continued perturbations can move the perihelion back into the planetary region where the object becomes a new visible comet with a semimajor axis still $\sim 10^4$ AU.

The major inconsistency between this picture of the formation of the Oort cloud and the orbit of our newly discovered object is the relatively small semimajor axis of the new object compared to the distance at which forces outside of the solar system should allow significant perihelion modification. Calculations show that a body with a semimajor axis of 480 AU and a perihelion in the planetary region should have only had its perihelion modified by 0.3% over its lifetime due to external forces (Fernandez 1997). Perihelion modification of such a tightly bound orbit requires a stellar encounter much closer than expected in the solar system's current galactic environment.

Only a small range of encounter geometries are capable of perturbing a scattered Kuiper belt-like orbit to this more Oort cloud-like orbit. As an example, an encounter of a solar mass star moving at 30 km s^{-1} perpendicular to the ecliptic at a distance of 500 AU will perturb an orbit with a perihelion of $\sim$30 AU and semimajor axis of $\sim$480 AU to one with a perihelion of 76 AU, like that seen. The need for a special geometry is not surprising, as any single stellar encounter would have a geometry that is unique. More difficult to explain, however, is that fact that in the present stellar environment, only one encounter so close is expected over the age of the solar system (Fernandez 1997). If the population of objects on large scattered orbits were in steady state the rarity of such an encounter would not matter, as the encounter could occur any time in the past 4.5 billion years. In reality, however, the number of highly elliptical orbits capable of being perturbed into the inner Oort cloud must have been significantly higher very early in the history of the solar system when the outer solar system was being cleared of icy planetesimals and the Oort cloud was being populated. The probability of a close stellar encounter so early is much less probable.

Nonetheless, if such a stellar encounter did indeed occur, its signature will be unmistakable in the orbital parameters of all subsequent objects found in this region. If all of the objects found in this inner Oort cloud region are consistent with the same unique stellar encounter geometry it will be clear that we are seeing the fossilized signature of this encounter.

4.3. Formation in a stellar cluster

Close encounters with stars would have been more frequent early in the history of the solar system if the sun had formed inside a stellar cluster. In addition, these encounters would have been at much slower speeds, leading to larger dynamical effects. In numerical simulations, Fernandez and Brunini (2000) found that early multiple slow moderately close encounters are capable of perturbing objects into orbits such as the one here. The process is identical to that hypothesized for the creation of the more distant Oort cloud, but in a denser environment the comets do not need to have as large of a semimajor axis before they are perturbed by the stronger external forces. Fernandez and Brunini predict a population of objects with semimajor axes between $\sim 10^2$ and $\sim 10^3$ AU, perihelia between ~ 50 and $\sim 10^3$ AU, large eccentricities (mean $\sim$0.8), and a large inclination distribution (a full-width-half-maximum of ~ 90 degrees) in this inner region of the Oort cloud formed in an early dense stellar environment.

We regard this scenario as the most likely for the formation of our newly discovered object. Formation of the solar system in a stellar cluster is a reasonable expectation (Clarke et al. 2000) for which potential evidence exists from other contexts (Goswami & Vanhala 2000). If indeed this scenario is correct, the orbits of any newly discovered objects in this region will unmistakably reflect this early history. The new discoveries will be widely spread in inclination and perihelion and will not be consistent with any special single stellar encounter geometry. As seen in the simulations of Fernandez and Bruini, the precise distribution of orbits in this inner Oort cloud will be indicative of the size of this initial cluster.

It is possible that a second such object is known already (or perhaps more). The scattered Kuiper belt object 2000 CR105 has a perihelion distance of 44 AU and a semimajor axis of 227 AU. Its present orbital configuration can be fully explained by a complex path involving migration of Neptune, scattering, and resonances (Gomes 2004), so its existence does not require any external forces. However, the cluster-formation scenario naturally leads to orbits such as that of 2000 CR105. The relatively small perihelion change of 2000 CR105 in this scenario is the consistent with the relatively modest semimajor axis of the object. Unfortunately, 2000 CR105 is close enough to the planetary region that it has possible suffered enough interaction to change its orbital parameters to erase the clear dynamical signatures we seek in this population.

5. Discussion

Each of the plausible scenarios for the origin of the distant object predicts a specific dynamical population beyond the Kuiper belt. With only a single object, though, little dynamical evidence exists for preferring any one scenario. With any new discoveries in this region, however, evidence should quickly mount.

We can make a simple order of magnitude estimate of the ease of future discovery of objects in this population. We find a single distant object in our survey while we have found 40 Kuiper belt objects discovered to date in the survey. Assuming the size distribution of the distant population is the same as that of the Kuiper belt, other surveys should find similar proportions, assuming they are equally sensitive to slow motions. As of 15 March 2004, 831 minor planets have been detected beyond Neptune, we thus expect to have seen $\sim$20 similar objects from other surveys. Even with this rough estimate, the lack of previous detection appears significant, suggesting either than most surveys have not been sensitive to motions as slow as $\sim$1.5 arcseconds per hour or that there is an overabundance of comparatively bright objects in the distant population. In either case, it appears likely that new objects in this population should be detected reasonably soon.

The most plausible scenario for the origin of our object appears to be the dynamical effect of the creation of the solar system within a dense stellar cluster. In this scenario the Oort cloud extends from its expected location at $\sim$100000 AU all the way in to the location of 2003 VB12. If this scenario is indeed correct the total mass of the Oort cloud must be many times higher than previously suspected. The expected population of large objects like the one discovered here is large. Our survey could only have detected this object during $\sim$1% of its orbit, suggesting a population of $\sim$100 objects on similar orbits. Moreover, if the population is nearly isotropic, $\sim$5 more such objects must be observable in the current sky, with a total population of 500. Assuming a size distribution similar to the Kuiper belt, the total mass of this population is $\sim$5 earth masses. The unseen population with ever more distant perihelia are likely even more numerous. With only the single object known in this population, extrapolation of a precise mass is not possible, nonetheless the existence of a nearby massive previously unsuspected inner Oort cloud appears likely. Even in the other origins scenarios a significant new mass must likely be present.

While the genesis of 2003 VB12 is currently uncertain, continued discovery and orbital characterization of similar high perihelion objects should allow a unique and straightforward interpretation of this population. Each hypothesized formation mechanism leads to the prediction of a different dynamically distinct population in the outer solar system. Study of these populations will lead to a new knowledge of earliest history of formation of the solar system.

We thank the staff at Palomar Observatory for their dedicated support of the the robotic operation of the Samuel Oschin telescope and the Palomar-QUEST camera. We are grateful to D. Stern, A. Dey, and H. Spinrad for obtaining critical followup observations at Keck Observatory and M. Schwartz of Tenagra Observatory for making his robotic telescope available for followup. We commend Project Pluto for making their fine orb_fit software freely usable by all. Re'em Sari has been inspirational in discussing scenarios of origin. This research is supported by a Presidential Early Career Award from NASA Planetary Astronomy.

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This preprint was prepared with the AAS LaTeX macros v5.2.

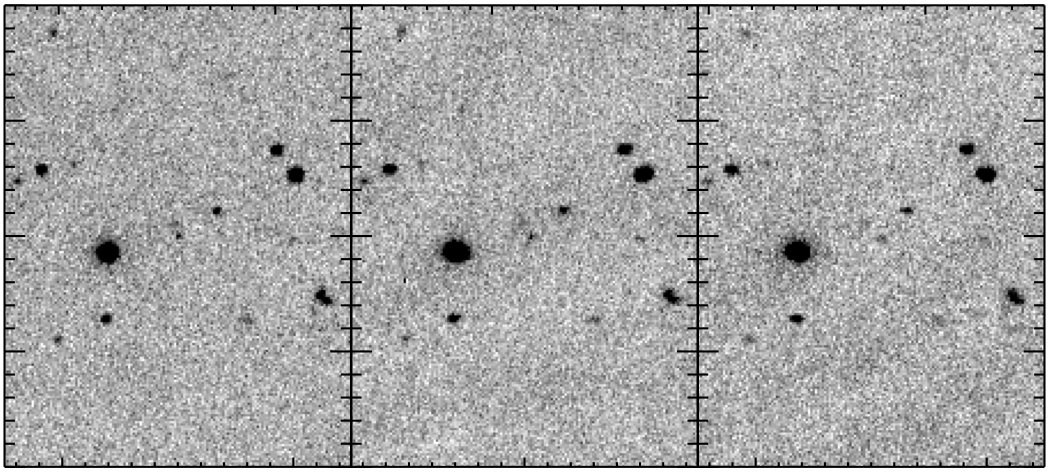
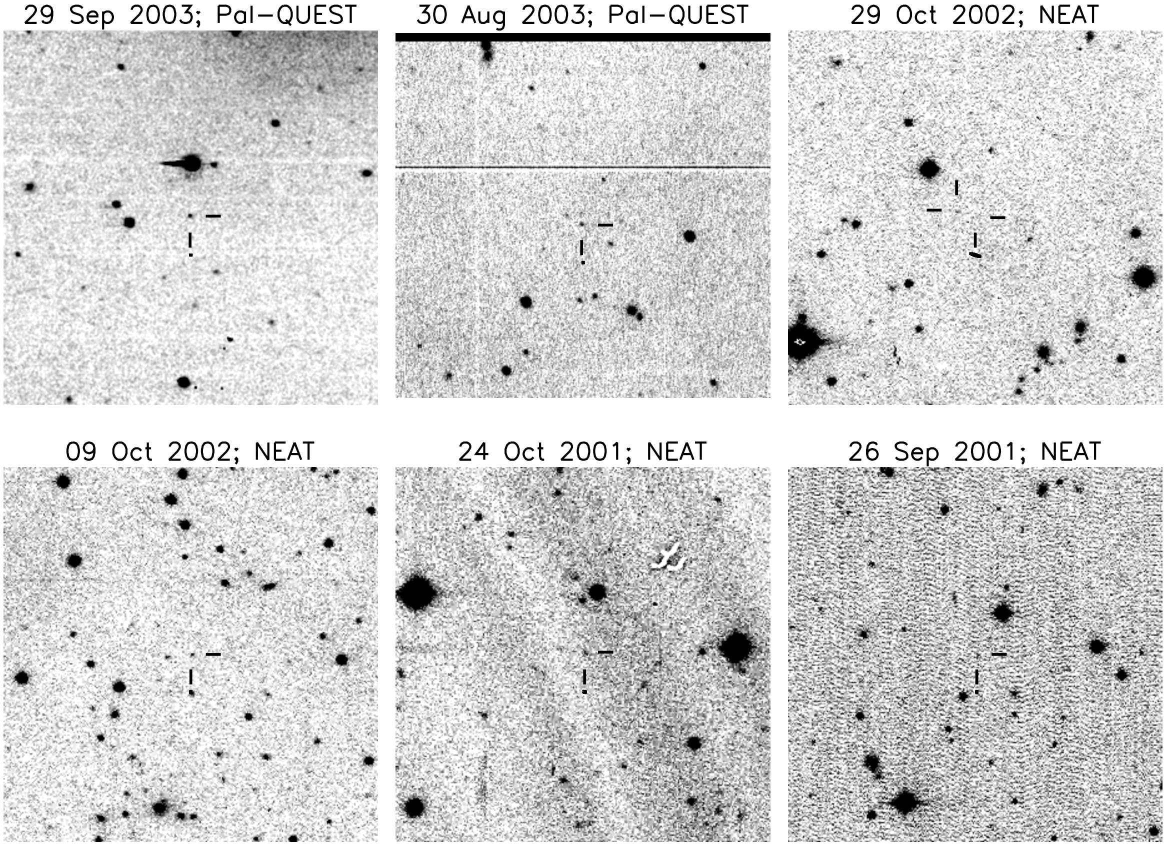


Fig. 1.— Discovery images of 2003 VB12 from the Palomar Samuel Oschin Telescope and the Palomar-QUEST camera. The pixel scale is 0.9 arcsecond per pixel with north up and east left. The 150 second exposures were obtained 14 November 2003 at 6:32, 8:03, and 9:38 (UT), respectively. The object moves 4.6 arcseconds over 3.1 hours.


29 Sep 2003; Pal–QUEST

30 Aug 2003; Pal–QUEST

29 Oct 2002; NEAT

09 Oct 2002; NEAT

24 Oct 2001; NEAT

26 Sep 2001; NEAT

Fig. 2.— Pre-discovery images of 2003 VB12. Each image shows a 5 by 5 arcminute field centered on the predicted position of 2003 VB12. The cross hairs mark the expected position, while the very small ellipse below the cross hairs show the size of the error ellipse. In all cases the object is well within the error ellipse and no similar object appears at the same position in any other data searched.