Occultations of HIP and UCAC2 stars down to 15\textsuperscript{m} by large TNO in 2004-2014

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Occultations of stars brighter than 15\textsuperscript{m} by largest TNOs are predicted. Search was performed using the following catalogues: Hipparcos; Tycho2 with coordinates of 2838666 stars taken from UCAC2 (Herald, 2003); UCAC2 (Zacharias et al., 2003) with 16356096 stars between 12.00 and 14.99 mag to the north from -45 declination. Predictions were made for 17 largest numbered transneptunian asteroids, recently discovered 2004 DW and 4 known binary Kuiper Belt objects. 64 events occurring at solar elongation of 30\textdegree{} and more are selected, including exceptionally rare occultation of 6.5\textsuperscript{m} star by double (66652) 1999 RZ\textsubscript{253} on 2007 October 4th. Observations of these events by all available means are extremely important since they can provide unique information about the size of TNOs and improve their orbits dramatically.

INTRODUCTION

Over 800 Transneptunian Objects (TNO) are discovered since 1992 with 67 of them being numbered and 7 having proper names as of February 2004. No reliable measurements of their sizes have been obtained so far. Angular sizes even of the largest objects are about 0.04\textquotedbl{}±0.01" (Quaoar) which is at the limit of Hubble Space Telescope resolution. Most size estimates are based on the indirect methods strongly dependant on assumptions. Albedoes 0.04-0.08 are generally supposed for TNOs, but they are definitely varying among different objects.

The only direct method to measure sizes of single TNOs at present is observing stellar occultations by them. Over 500 occultations of stars by Main Belt asteroids have been observed so far, with 17\% of them having 5 or more chords measured. For some objects size and shape were determined with an equivalent angular resolution of 0.002".

OCCULTATIONS BY TNO

TNOs are typically at 30-50 AU distances from the Earth corresponding to 0.2"-0.3" parallax. This means that occultation will only happen somewhere on the Earth if the geocentric path of the object passes within 200-300 mas from the star. Combined with a very slow angular motion of TNO (0.1-1 mas per second of time) it makes rate of stellar occultations by them about three orders of magnitude smaller than by main belt asteroids and about 100 times less than that of Jovian Trojans, approximately inversely proportional to (a-1)\textsuperscript{2}.

Estimates show that any given TNO will occult a star brighter than 15\textsuperscript{m} on average approximately every 4 or 5 years. For ~10\textsuperscript{5} HIPPARCOS stars brighter than 10-11\textsuperscript{m} we should be expecting one occultation in 10 years by 20 largest transneptunian objects, and only one event per century for ~10\textsuperscript{4} stars brighter than 6.5\textsuperscript{m}.
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STAR CATALOGUES ACCURACY

Error in coordinates of occulted star will significantly increase the uncertainty of both event time and position. At 40 AU distance, 1 milliarcsecond is corresponding to 30 km. 0.25" error in star coordinates will shift the occultation path by ~1 Earth radius. Since the positions of Transneptunian objects are known to 0.25" uncertainty, 0.05" accuracy of the star coordinates will be acceptable. Before 2003, coordinates were known to milliarcsecond accuracy for ~100000 stars in HIPPARCOS catalogue. Tycho2 catalogue including ~2 Mln stars usually brighter than $12^m$ is essentially a by-product of the same HIPPARCOS project. It has systematic and statistical errors typically within 0.1"-0.2" but reaching 0.5"-1.0" in some fields. Thus Tycho2 is not satisfactory for predicting occultations by TNO.

Situation in astrometry was revolutionized in 2003 with the release of 2nd USNO CCD Astrograph Catalogue UCAC2 (Zacharias et al.) with coordinates and proper motions for 48 Mln stars between $8^m$ and $16^m$. Position errors of $12^m$ stars in UCAC2 are 15-20 mas and 40-50 mas for $15^m$. This catalogue does not cover areas to the north from +45..+52 declination, but that is not a problem since no objects involved in current search will reach ±45 declination during next 10 years.

PREDICTIONS FOR 2004-2014

Occultations from 2004 Jan 27 to 2014 Dec 31 were computed for the following objects:

a) Recently discovered largest known TNO 2004 DW with absolute mag $H_0$=2.2-2.4;

b) 17 numbered objects with $H_0$<5.5

2.6 (50000) Quaoar
3.2 (28978) Ixion

Single body diameters were calculated from $H_0$ by the formula $\log D[\text{km}]=3.52-0.2*H_0$. This corresponds to assumed albedo of 0.16 and is a conservative estimate. For (50000) Quaoar this formula gives 1000 km which is in a good agreement with the lower limit from Hubble direct imaging (1260±300 km). If albedo is 0.04, actual size of TNO will be exactly twice the value listed in table. For binary asteroids with two bodies of the same size and albedo diameter of each component will be 0.71*$D$.

Orbits of selected TNO from 2004 Jan. 27th version of astorb.dat (Bowell, 2004) were integrated through the end of 2014 and all geocentric conjunctions within 0.5" to HIP and UCAC2 stars were found. For the year 2004 occultations by 36 largest unnumbered objects with $H_0$<5.5 were also computed and 9 events have been found. Mean value of current ephemeris uncertainty (CEU) was 0.26" for the numbered objects and 1.0" for unnumbered ones.
Results of the search are presented in table. Intervals of time (rounded to 5 minutes) are given when occultation may happen on the night part of Earth with 0.25" uncertainty at both sides already taken into account. Due to the different speed of TNOs relative to Earth (from 25 km/s at opposition to 5 km/s and even less near the stationary point) these interval may vary from ~10 minutes to 1.5 hour in case of Varuna occultation in 2012. For double asteroids extra 0.25" were added since orbital distances in these pairs are also estimated as 6-8 thousand km.

Exceptional occultation of 6.5m K0 star HIP 111398 = HD 213780 = SAO 146161 = ZC 3313 in Aquarius by binary object (66652) 1999 RZ253 in 2007 should be noted. Additional observations of this TNO on the largest telescopes are extremely important to predict the separation and positional angle of components at the epoch of the event. International campaign involving observers in Australia, New Zealand, China, Japan, eastern Russia and Hawaii should be organized to measure the sizes and shape of this binary system.

Finder charts and preliminary path plots for occultations listed here are available at http://hea.iki.rssi.ru/~denis/TNOocc.html or by E-mail request to denis@hea.iki.rssi.ru.

OBSERVING METHODS

Observations can be performed by several techniques and different kinds of equipment. In principle, highest temporal resolution is not necessary for occultations by TNO. With event durations about several dozen seconds and even 2-3 minutes in some cases, 1-3 sec integration time will already give the unprecedented chord measurement accuracy. This is why one can use CCD imaging, CCD in drift-scan mode, photometers, high-sensitivity videocameras and even visual observations with stopwatch. CCD readout time should be reduced to minimum by binning pixels and exposing small window instead of full frame. Optimal exposure time should be selected depending on the magnitude of occulted star and detector sensitivity. Precise absolute timing of star disappearance and reappearance is not critical since with 5-10 minutes uncertainty of event time even 1-second accuracy will improve the orbital position by two orders of magnitude. For bright occultations fast photometers can provide the measurements of occulted star diameter at unprecedented angular resolution. Since TNOs are moving at 0.1-1 mas/sec rate (500-5000 times slower than the Moon), new close binaries can be discovered which are impossible to resolve by any other methods.

DISCUSSION

Search was intentionally limited to the largest objects with ephemeris uncertainty of 0.3" or better. Although smaller objects might (and definitely will!) occult brighter stars, detection probability of those events would be much smaller compared to those listed here. It is preferrable to concentrate on 2-5 "special" events each year. Success can only be achieved by the joint efforts planned well in advance. Worldwide observations by as many telescopes as possible are necessary. Prediction of events till 2014 will allow to make changes in tight observing schedules at the large scopes. Additional observations of selected TNOs to improve ephemeris and prediction accuracy are also encouraged. New large objects will definitely be found in the nearest future. Predictions of occultations by them will be posted at author’s site together with updates on those listed here.
Positive observation of stellar occultation by TNO will make significant impact in several areas of astronomy at once. It will allow to:
- measure the size and shape of these distant objects directly which is impossible by other means;
- give indications on their composition, and together with estimates of masses in binary systems directly determine their density;
- improve orbital position by 10-50 times assisting possible space missions to TNO;
- provide unique information valuable for understanding the theory of Solar system evolution;
- discover probable close binary objects with the separations between components of the order of 1000 km.

ACKNOWLEDGEMENTS

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### OCCULTATIONS OF STARS BY TNO 2004-2014

| Date of event | Time (UT) | Asteroid name | size (km) | Dur (sec) | Star Name | R.A. (2000.0) | Dec  |
|---------------|-----------|----------------|-----------|-----------|-----------|---------------|------|
| 2004 Jan 29   | 23:35-23:55 | 2003 AZ84 | 568 | 23.4 | 2UCAC 36806754 | 07 12 19.883 | +14 04 20.02 | 14.5 |
| 2004 Feb 14   | 22:10-22:35 | 2001 XR254 | 255 | 14.2 | TYC 1343-00785-1 | 06 54 14.687 | +21 37 48.10 | 11.6 |
| 2004 Mar 07   | 03:15-03:30 | 2000 CO105 | 268 | 14.7 | 2UCAC 39141168 | 08 23 16.013 | +20 33 01.42 | 12.3 |
| 2004 Mar 08   | 02:10-02:25 | 1999 CC158 | 241 | 11.6 | 2UCAC 40185292 | 09 15 58.264 | +23 38 56.76 | 13.7 |
| 2004 Mar 20   | 13:35-13:45 | 1996 TL66 | 275 | 10.5 | 2UCAC 36322084 | 03 00 28.306 | +12 40 40.89 | 13.4 |
| 2004 Mar 27   | 00:20-00:40 | 2002 KW14 | 302 | 21.2 | 2UCAC 24857550 | 15 34 29.721 | -18 18 28.41 | 13.6 |
| 2004 Apr 07   | 10:30-11:00 | 2001 KD77 | 252 | 24.7 | 2UCAC 23658681 | 16 58 51.823 | -20 36 51.67 | 11.7 |
| 2004 Jun 26   | 19:55-20:05 | Chaos | 347 | 11.6 | 2UCAC 40137180 | 04 08 53.436 | +23 56 34.41 | 13.2 |
| 2004 Jun 29   | 18:25-19:10 | 1997 CQ29 | 158 | 9.5 | 2UCAC 34467578 | 11 04 07.504 | +07 39 54.56 | 14.5 |
| 2004 Aug 08   | 23:15-23:30 | 2001 QD298 | 257 | 10.5 | 2UCAC 24989527 | 12 52 30.098 | +11 59 33.61 | 14.3 |
| 2005 Mar 13   | 21:25-21:35 | 2002 UX25 | 631 | 21.6 | 2UCAC 28298467 | 22 29 21.656 | -10 02 41.04 | 14.9 |
| 2005 Aug 04   | 04:20-04:35 | 1995 SM55 | 363 | 16.6 | 2UCAC 39255131 | 02 07 19.531 | +25 33 26.70 | 14.4 |
| 2005 Oct 24   | 08:05-08:30 | 1998 SM165 | 229 | 9.4 | 2UCAC 33162437 | 13 31 09.061 | +04 23 37.99 | 11.7 |
| 2005 Dec 07   | 09:15-09:35 | 1999 KR16 | 380 | 17.9 | 2UCAC 30864992 | 14 20 27.168 | +02 54 42.58 | 13.7 |
| 2006 Jun 18   | 20:25-20:50 | 2002 VE95 | 288 | 15.8 | 2UCAC 35331886 | 04 14 47.942 | +10 08 18.19 | 13.0 |
| 2006 Jul 26   | 07:55-08:25 | Ixion | 759 | 55.9 | 2UCAC 111398 | 22 34 06.604 | +09 36 30.64 | 6.5 |
| 2006 Oct 07   | 19:30-19:45 | Ixion | 759 | 36.0 | 2UCAC 22946030 | 16 35 05.045 | -22 11 08.86 | 13.8 |
| 2007 Aug 04   | 04:20-04:35 | 2002 VE95 | 288 | 15.8 | 2UCAC 35331886 | 04 14 47.942 | +10 08 18.19 | 13.0 |
| 2007 Oct 04   | 11:10-11:50 | 1999 RZ253 | 219 | 11.2 | HIP 111398 | 22 34 06.604 | +09 36 30.64 | 6.5 |
| 2008 Jan 22   | 06:55-07:30 | Chaos | 347 | 26.0 | 2UCAC 40810575 | 04 21 06.919 | +25 33 26.70 | 10.8 |
| 2008 Feb 11   | 04:20-04:40 | Varuna | 603 | 28.8 | TYC 1913-00670-1 | 07 18 50.100 | +25 43 19.31 | 11.3 |
| 2008 Sep 10   | 12:25-13:15 | Quaoar | 1000 | 149.5 | 2UCAC 26249129 | 17 05 49.913 | -15 20 44.26 | 13.7 |
| 2008 Sep 30   | 07:20-07:40 | Ixion | 759 | 44.6 | 2UCAC 22946420 | 16 44 05.610 | -23 18 07.11 | 13.6 |
| 2008 Oct 07   | 19:40-19:55 | Ixion | 759 | 37.3 | 2UCAC 22946543 | 16 44 33.933 | -23 19 19.45 | 12.8 |
| 2008 Dec 07   | 01:55-02:20 | Varuna | 603 | 29.0 | 2UCAC 40846256 | 07 29 48.171 | +25 40 07.71 | 14.8 |
| 2009 Mar 10   | 08:25-08:40 | 2002 VE95 | 288 | 19.7 | 2UCAC 34960757 | 04 17 00.297 | +09 18 45.63 | 13.3 |
| 2009 May 01   | 13:50-14:15 | Quaoar | 1000 | 54.1 | 2UCAC 26252549 | 17 18 12.542 | -15 24 49.90 | 14.3 |
| 2009 Jul 18   | 04:40-04:50 | 2002 VE95 | 288 | 10.8 | HIP 21308 | 04 34 30.274 | +10 00 58.46 | 7.7 |
| 2009 Aug 22   | 10:40-11:15 | 2002 UX25 | 631 | 68.5 | 2UCAC 35326247 | 02 09 00.114 | +10 07 56.40 | 14.1 |
| 2009 Sep 25   | 11:05-11:30 | 1995 TL8 | 275 | 15.1 | TYC 1223-00579-1 | 02 40 23.728 | +15 46 01.74 | 11.6 |
| Date of event | Time    | Asteroid | size | Dur | Star      | R.A. (2000.0) | Dec         | Mag  |
|--------------|---------|----------|------|-----|-----------|---------------|-------------|------|
| 2009 Oct 09  | 10:15-10:35 | 2002 TX300 | 724  | 28.6 | 2UCAC 41650964 | 00 37 13.610 +28 22 22.98 | 13.1 |
| 2009 Oct 15  | 17:55-18:10 | Quaoar    | 1000 | 45.8 | 2UCAC 26023237 | 17 12 33.132 -15 30 54.97 | 15.0 |
| 2010 Feb 19  | 22:55-23:20 | Varuna    | 603  | 32.3 | TYC 1914-00301-1 | 07 29 22.470 +26 07 23.23 | 11.0 |
| 2010 Jul 19  | 01:35-02:05 | Ixion     | 759  | 42.4 | 2UCAC 22032118 | 16 54 25.862 -24 24 22.86 | 11.5 |
| 2011 Feb 22  | 02:25-02:50 | 1995 TL8  | 275  | 18.3 | 2UCAC 37301105 | 02 39 37.120 +15 41 48.75 | 13.6 |
| 2011 Jun 01  | 11:05-11:25 | Ixion     | 759  | 30.3 | 2UCAC 21584537 | 17 03 39.446 -25 01 27.82 | 14.7 |
| 2011 Aug 03  | 22:35-23:10 | 1999 RZ253 | 271  | 19.8 | 2UCAC 29387410 | 22 59 38.963 -07 02 53.38 | 14.6 |
| 2011 Nov 04  | 00:35-00:50 | Quaoar    | 1000 | 35.9 | 2UCAC 26027484 | 17 24 23.771 -15 38 43.34 | 14.6 |
| 2011 Dec 18  | 11:40-12:50 | 1999 TC36 | 347  | 40.7 | 2UCAC 32137136 | 01 35 51.911 +01 13 15.69 | 14.1 |
| 2012 Apr 16  | 04:20-04:55 | Ixion     | 759  | 55.9 | TYC 6816-00401-1 | 00 37 13.610 +28 22 22.98 | 13.1 |
| 2012 May 01  | 03:35-03:55 | 1999 RZ253 | 219  | 10.2 | 2UCAC 29759182 | 23 04 54.428 -06 29 06.50 | 14.9 |
| 2012 Jun 04  | 01:10-01:30 | 1996 QQ21 | 302  | 14.0 | 2UCAC 28386513 | 02 40 01.570 +02 31 43.27 | 14.7 |
| 2012 Oct 07  | 04:30-04:55 | 2002 AW197 | 724  | 30.2 | 2UCAC 32701289 | 17 12 26.791 -25 34 10.85 | 10.8 |
| 2012 Oct 28  | 19:50-21:25 | Varuna    | 603  | 144.8| 2UCAC 41016878 | 07 53 29.509 +26 05 51.86 | 13.4 |
| 2013 Jan 29  | 06:10-06:30 | Varuna    | 603  | 24.2 | 2UCAC 41187592 | 16 54 25.862 -24 24 22.86 | 11.5 |
| 2013 Feb 18  | 11:40-12:50 | Chaos     | 347  | 93.9 | 2UCAC 41496855 | 04 49 59.491 +27 50 52.79 | 14.4 |
| 2013 May 28  | 18:35-18:55 | 1999 KR16 | 229  | 10.1 | 2UCAC 29288802 | 15 13 08.695 -07 07 13.91 | 11.7 |
| 2013 Jun 02  | 22:20-22:35 | Ixion     | 759  | 30.4 | 2UCAC 21137706 | 17 14 19.280 -26 08 23.27 | 14.4 |
| 2013 Oct 23  | 13:20-13:35 | Ixion     | 759  | 31.3 | 2UCAC 21137306 | 17 10 57.419 -26 07 23.91 | 14.2 |
| 2013 Dec 06  | 09:10-09:20 | Huya      | 380  | 11.0 | TYC 5025-00448-1 | 15 39 28.493 -05 37 11.16 | 10.1 |
| 2013 Dec 20  | 14:05-14:40 | 2002 TX300 | 724  | 55.4 | TYC 2276-01081-1 | 00 52 46.890 +31 03 39.18 | 11.4 |
| 2013 Dec 27  | 17:20-17:50 | 1995 SM55 | 363  | 23.4 | 2UCAC 42006839 | 02 40 01.674 +29 27 23.90 | 13.3 |
| 2014 Jan 24  | 01:35-01:50 | Quaoar    | 1000 | 34.9 | 2UCAC 26041319 | 17 43 03.235 -15 45 10.63 | 14.6 |
| 2014 Mar 01  | 16:30-16:45 | 2004 DW   | 1200 | 45.9 | TYC 5476-00882-1 | 09 58 22.549 -08 16 55.27 | 12.1 |
| 2014 Mar 10  | 15:25-15:55 | 1997 CQ29 | 158  | 6.3  | 2UCAC 32542503 | 11 58 36.918 +02 28 27.68 | 11.9 |
| 2014 Apr 15  | 01:50-02:00 | 1996 TL66 | 275  | 9.9  | 2UCAC 34961430 | 04 26 07.463 +09 23 13.78 | 14.7 |
| 2014 Jul 24  | 14:20-15:10 | Huya      | 380  | 51.0 | TYC 5024-00589-1 | 15 36 41.149 -04 36 29.35 | 11.7 |
| 2014 Aug 14  | 21:40-22:40 | 1996 QQ21 | 302  | 48.1 | HIP 75882  | 15 29 58.355 -10 03 19.73 | 9.1  |
| 2014 Sep 13  | 08:35-09:20 | 2002 VE95 | 288  | 27.1 | 2UCAC 34784210 | 05 31 16.439 +08 55 17.49 | 12.3 |
| 2014 Oct 20  | 14:45-15:25 | 1999 RZ253 | 219  | 12.4 | 2UCAC 29941401 | 23 09 49.521 -05 59 47.15 | 14.5 |
| 2014 Nov 08  | 22:00-22:15 | Quaoar    | 1000 | 35.4 | 2UCAC 26039148 | 17 40 27.392 -15 41 59.91 | 13.9 |