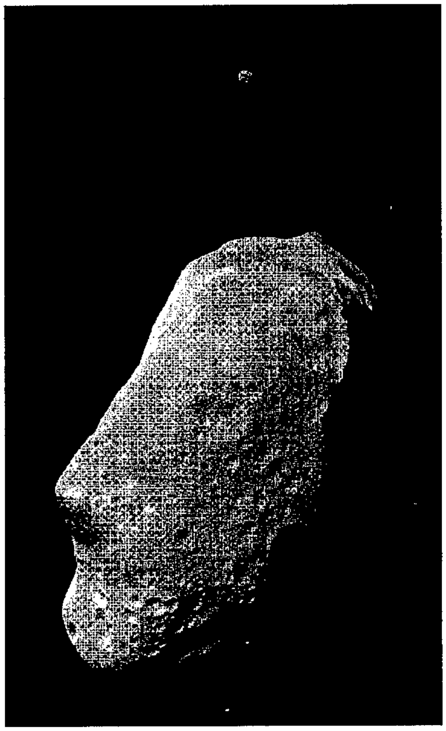
# Predicting How Close Near-Earth Asteroids Will Come to Earth in the Next Five Years Using Only Kepler's Algorithm



1 April, 1998

Melissa Jean Wright

Master of Space Operations

**REPORT DOCUMENTATION PAGE**

*Form Approved*
*OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
26.Oct.98

**3. REPORT TYPE AND DATES COVERED**
MAJOR REPORT

**4. TITLE AND SUBTITLE**
PREDICTING HOW CLOSE NEAR-EARTH ASTEROIDS WILL COME TO EARTH IN THE NEXT FIVE YEARS USING ONLY KEPLER'S ALGORITHM

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**
2D LT WRIGHT MELISSA J

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
UNIVERSITY OF COLORADO AT COLORADO SPRINGS

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
98-020

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION AVAILABILITY STATEMENT**
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

**14. SUBJECT TERMS**

**15. NUMBER OF PAGES**

**16. PRICE CODE**

**17. SECURITY CLASSIFICATION OF REPORT**

**18. SECURITY CLASSIFICATION OF THIS PAGE**

**19. SECURITY CLASSIFICATION OF ABSTRACT**

**20. LIMITATION OF ABSTRACT**

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

# Abstract

*There are estimated to be over 150,000 near-earth asteroids in our solar system that are large enough to pose a significant threat to Earth. In order to determine which of them may be a hazard in the future, their orbits must be propagated through time. The goal of this investigation was to see if using only Kepler's algorithm, which ignores the gravitational pull of other planets, our moon, and Jupiter, was sufficient to predict close encounters with Earth. The results were very rough, and about half of the closest approaches were near the dates of those predicted by more refined models. The distances were in general off by a magnitude of ten, showing that asteroid orbits must be very perturbed by other planets, particularly Jupiter, over time and these must be taken into account for a precise distance estimate. A noted correlation was that the difference in the angular distance from the* ***I*** *vector was very small when the asteroid and Earth were supposed to be closest. In conclusion, using Kepler's algorithm alone can narrow down intervals of time of nearest approaches, which can then be looked at using more accurate propagators.*

# Table of Contents

Page

## Figures

## Tables

# Background

An asteroid is a large chunk of rock, which can vary in size, color and composition. No one is certain how they were created, but asteroids are probably remnants of early solar system formation, or broken off parts of larger asteroids [1]. The main asteroid belt in our solar system consists of 95% of all known asteroids and exists between Mars and Jupiter, at a distance of 2.0 - 3.3 AUs from the Sun. Jupiter, being the heaviest of the planets, keeps this belt in its place. Its high gravitational attraction has prevented these numerous pieces of solar system rubble, whose total mass is less than the moon's [2], from becoming one body [3]. Instead, Jupiter's gravitational attraction has sped up many of the asteroids over time, causing them to collide with one another and form smaller pieces. Its pull forces many asteroids to change their orbits over years; they can end up shooting out of the solar system or into the inner, sometimes becoming near-Earth orbiters. Most rocks seem to be "in simple rotation with a fixed pole" [4] and have a period of 2 – 60 hours, the average being eight hours [5]. There are over 1 million that are larger than 1km, the biggest of them all being Ceres, which is 950 km in diameter. Luckily, it comes nowhere near Earth. Figure 1 [6] shows Ida, a 52-km main belt asteroid. The craters from other asteroids striking it are visible.

*Figure 1*

Asteroids and comets that have orbits which cross that of the Earth's are called near-Earth objects, or NEOs. Of these, approximately 10 percent are classed as long-period comets, which return every twenty years or more [6]. Asteroids whose orbits cross, or eventually will cross, that of the Earth's are termed near-Earth asteroids (NEA s) or Earth-crossing asteroids (ECA s). Those discovered so far range in size from 109 meters to 32 kilometers; there are doubtlessly asteroids much smaller than this, it is just very hard to uncover them. Most likely, there are some as huge as 3 to 5 km yet to be detected [7]. The largest ECA is 1627 Ivar, which is 8 km in diameter [8]. ECAs obviously have the greatest likelihood of all NEOs in colliding with the Earth. Although most of them will end up being ejected from the Solar System thanks to Jupiter's pull, some will strike a planet. One-third of these will hit Earth. About 250 ECAs have been discovered, but it has been estimated that there are thousands more. Approximately 1000-4000 ECAs are bigger than 1 kilometer (the minimum global catastrophe threshold – see Introduction), 5,000 - 20,000 larger than 500 meters, 150,000 - 1 million larger than 100 meters, and 10 million - 1 billion bigger than 10 meters [6]. Asteroids smaller than 10 meters are of little significance since they burn up passing through the Earth's atmosphere if they happen to run into it. Figure 2 [9] on the next page is a plot of the orbits of the hundred largest known ECAs, or only 5% of all known ECAs. It shows how congested the area around Earth can be. The dot in the center represents the Sun and Mercury's orbit is the dotted line closest to it. The outermost dotted line is Mars and Venus and Earth's are hard to see because the ECA orbits obscure them.

The near-Earth category of asteroids contains many different types; some primarily metal, others stony minerals, and still others composed of primitive early solar system matter [6]. They come from the main-belt asteroids "through collisional fragmentation and chaotic dynamics" [8]. But ECAs don't have to originate from the asteroid belt; they can also be

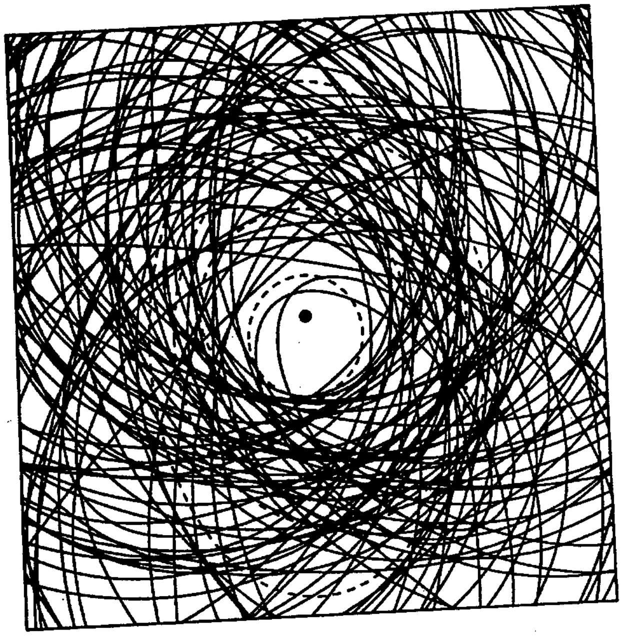
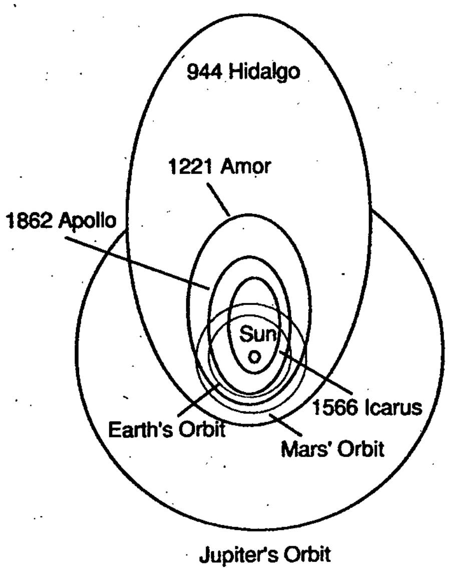


*Figure 2*

comets that can no longer produce a tail. After persistent close approaches to the Sun, these comets have burned up all volatile material [5]. ECAs also vary in spectral type, or brightness. Astronomers think that most of the brighter, larger ECAs, which are easier to spot, have already been discovered.

Within the ECA group, there are four divisions; Aten, Amor, Apollo and Arjuna. Aten asteroids have periods of less than one year and the majority of their orbit is within the Earth's, although they can cross parts of the Earth's orbit. Amor asteroids frequently cross Mars' orbit and approach ours. They may approach Earth as their orbits change over time, but currently present little threat. Apollos have their perihelion within the Earth's orbit, so that they frequently cross it, and a period longer than a year. They are most liable to collide with us. Figure 3 [6] on the next page compares the orbits of 1862 Apollo and 1566 Icarus, which are Apollos, and 1221 Amor, which is an Amor, to that of Earth. Finally, Arjuna asteroids have circular orbits within the Earth's and are smaller than 100 meters in size. This is a fairly new group, founded in 1994, and some claim these asteroids should instead be classed as Atens [6]. Scientists have

*Figure 3*



ascertained that around 65 percent of the ECAs are Apollos, 25 percent Amors and 10 percent Atens [6].

In the past, astronomers determined the orbits and classes of asteroids using a 0.46-m Schmidt telescope [10]. But 0.9-meter telescopes, such as the one used by the Spacewatch program, are replacing these. The Arizona-based Spacewatch tends to find around two to three new near-Earth objects per month. Spacewatch is a project that specifically sets out to track as many ECAs as possible and is the only program in the world with this sole goal. A charge-coupled device (CCD) camera is used with an exposure time of 2.5 minutes. Any object that moves shows up as a streak on the film and is picked out by a computer [11]. In Figures 4 [12] and 5 [1] the asteroid in each shows up as a band. Either a long-exposure image (Fig. 4) or its negative (Fig. 5) can be used. A 0.9-meter telescope scans the same region of sky in half-hour intervals three times. In order to have accurately measured positions, a newly discovered object should be reobserved on another night. Only then should the preliminary orbit be determined.

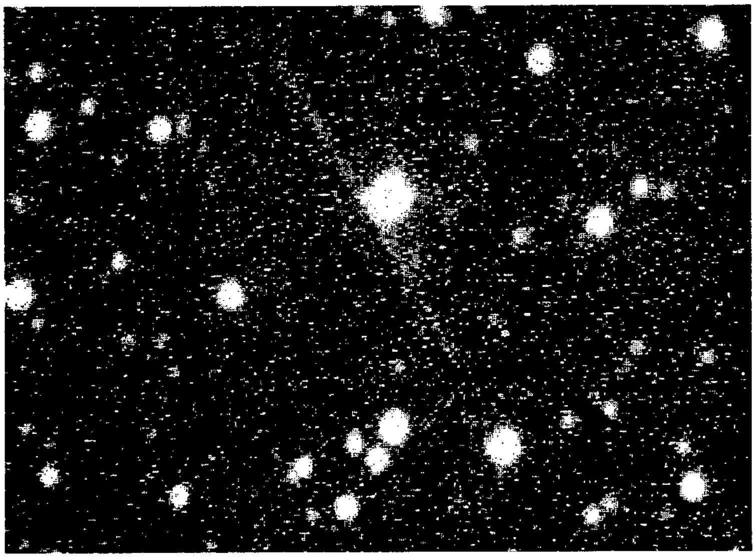


*Figure 4*

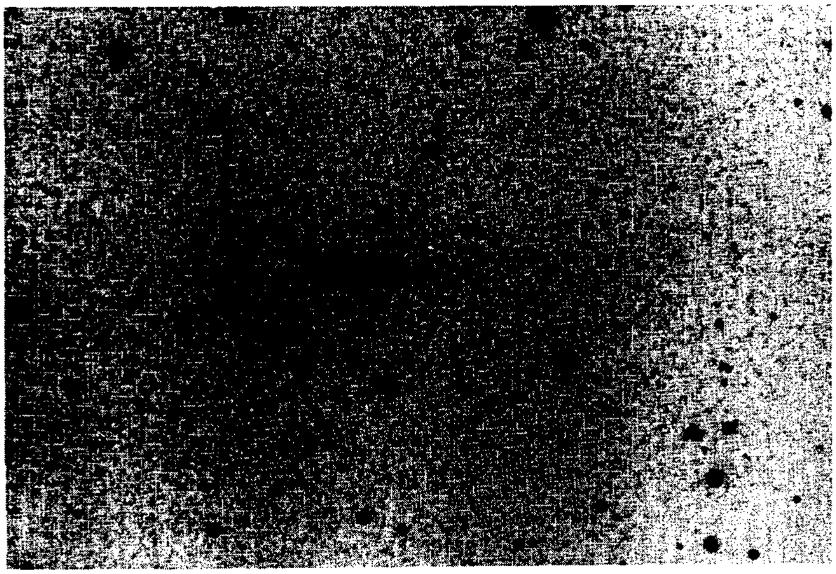


*Figure 5*

Astronomers have missed some asteroids, such as 1993 KA2, until they were very close. 1993 KA2 was 5 to 11 meters across and passed Earth less than halfway to the moon, 140,000 km or 0.0009 AUs, before it was noticed [6]. Many are missed because they are relatively small or approach from a sunward direction, making it near impossible for telescopes to pick them up [5].

The threat of asteroids was a hot topic last month when Spacewatch's James Scotti unearthed the perhaps-menacing asteroid 1997 XF11 [13]. At first, he forecast that it was on a straight collision course with Earth in 2028, soon changing that to coming within one-tenth of the distance to the moon. But he can't take into account any unexpected perturbations that may occur in the next few years and bring the asteroid even closer. There may be some sort of random gravitational perturbation such as a shock wave from a supernova or a collision with another asteroid. This demonstrates how hard it is to accurately predict a close encounter.

Once forecasts are as precise as possible, we can be on the lookout for a close approach and prepare for a potential collision. We can take steps to stop what could be a world disaster by investigating possible solutions such as nuclear deflection or fragmentation of the asteroid using pyrotechnic charges. This is why collision forewarning is so important; if a 1-km rock is hurtling our way it does not have to mean the end of the world.

## Introduction

In order that we are aware of which asteroids may approach Earth dangerously close and be able to prepare possible defenses, the asteroid orbits must be determined. This can become quite involved and complicated. Perturbations on the orbits by Jupiter, Mars, the earth and even the moon must be considered. Most studies include forces from all of the other planets. Each orbit's line of apsides tends to advance slightly, particularly for orbits with small semimajor axis and large eccentricities [14]. My goal in this investigation is to predict which asteroids might threaten Earth in the next five years using only the simple Kepler algorithm, which propagates true anomalies, and thus orbits, through time. I want to see if it is possible to get a rough idea of when a potentially threatening asteroid may approach the Earth without taking into account the gravitational pull of the other planets and line of apsides advancement. I have the results from models that did include every perturbation with which to compare my calculations. I will assume a "close" approach to be less than 0.1 AUs [15], or 39 times the distance to the moon, because there is a risk at this distance that a slight change to an asteroid's orbit would bring it even nearer to Earth. The size of the asteroids I look at also establishes whether or not they are going to be hazards.

It is generally agreed [9] that the minimum global catastrophe threshold for asteroids is 1-km. If one this size were to strike Earth, there would be a severe greenhouse effect, 500km/hr plus winds, Tsunamis (large tidal waves), acid rain, triggered volcanism, darkness and cold. Most of these would last several months. A minimum of 25% of the world's population would be expected to die [9]. A smaller 100-meter asteroid would be expected to kill 1 million people; most from Tsunamis, the rest from the impact. Because of the number of people an asteroid might kill, we have more of a chance of dying as a result of one hitting Earth than of dying in a

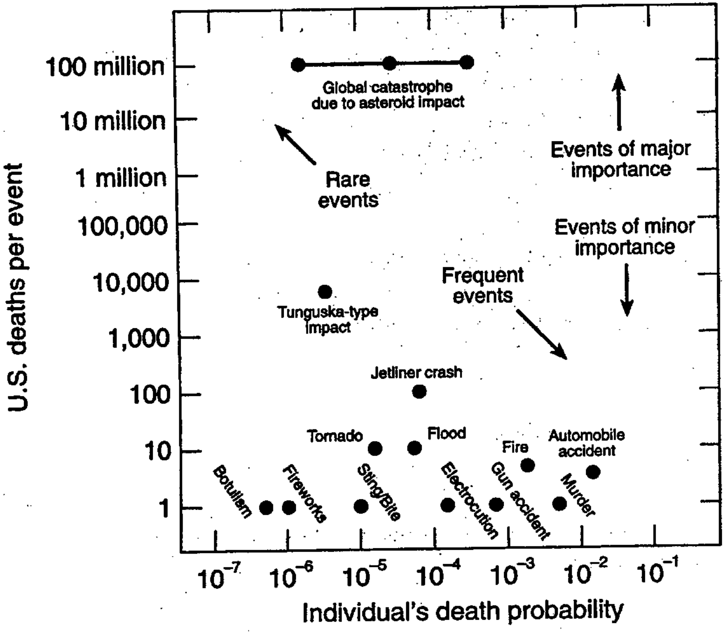


*Figure 6* [16]

plane crash, or 1 in 10,000 (see Figure 6). So I am only going to look at asteroids larger than 0.1-km, which would be expected to significantly effect us if they landed here.

Finally, the maximum effect Jupiter could have on any given asteroid will be calculated, to see if it would change my results significantly, particularly for those asteroids that pass close to it.

## Specific Topics of Review

As mentioned before, in this study I use Kepler's algorithm to propagate orbits. The positions of particular asteroids as well as that of the Earth are predicted in time intervals of ten days for five years. A smaller time period would take far more calculations and a longer one might miss a close encounter. Looking at more than five years would mean the gravitational effects I am ignoring would take on a greater significance. At the chosen times, I computed the distance between the Earth's position vector (to the Sun) and the asteroid's position vector.

The asteroids I investigated included those that have already been predicted to pass near the Earth in the next five years by NASA (Appendix I). Their predictions, which gave the Julian date and distance of closest approach, certainly took into account any movement of the line of apsides and any gravitational forces from other bodies, unlike my two-body problem. I then compared my results with theirs. I also randomly picked a few other NEAs to see what their closest approaches may be.

To begin with, I needed the orbital elements of the asteroids and of the Earth as inputs for the Kepler algorithm. For the asteroids, I utilized a chart from the Internet (Appendix II). It gives the accurate orbital elements of semi-major axis (a) in AUs, eccentricity (e), inclination (i) in degrees, longitude of ascending node ($\Omega$), argument of perigee ($\omega$) and true anomaly (M), all in degrees. They are given at JD 2449800 (March 23, 1995) for all asteroids discovered up until April 1995. Their orbits were determined after several sightings of each asteroid, using the sun as the focus. Usually three observations of an asteroid's position vector are sufficient [17] to get orbital elements, but sometimes many more, up to hundreds, are needed because the accuracy of the measurements is not good enough. For the Earth, I used orbital elements at JD2000 (Jan 1, 2000) [22].

As the Earth and asteroids move through time, their true anomalies change. The true anomaly $\nu$ is the angle from the vector **e**, which points to the perihelion, to the position vector **R** (see Figure 6). Other orbital elements, such as inclination and longitude of ascending node, change very slightly over time. I calculated i for the Earth over a time period of a year and the change in it was around a hundredth of a degree. However, since I am only dealing with five years and the orbits are rather large (unlike satellites orbiting Earth), I assumed the changes of all but the true anomalies to be negligible.

I came up with a C program (Appendix III) that would perform all the calculations I needed, taking in the orbital elements of an asteroid and coming up with an answer for the distance between that asteroid and the Earth at a particular point in time. Firstly, I wrote the function *Anomaly* to propagate the true anomalies of the asteroid and Earth. This was accomplished using the algorithm KepEqtnE [21], which required inputs of the eccentricity and the mean anomaly. Before the mean anomaly was sent to the function, it had to be converted to radians and calculated for the initial start date, which I chose to be April 1, 1998 (JD 2450905). This meant the asteroid Ms had to be propagated forwards and the Earth's backwards, using:

$$M_{new} = M + n^*\Delta t$$

Where $n$ = mean motion = $\sqrt{}(\mu / a\hat{}3)$ (a was given in the charts in AUs & I changed it to km)
($\mu$ is the gravitational parameter for the Sun)
and $\Delta t$ = the time change in seconds.

Once both mean anomalies were set for the correct date, they were sent to the *Anomaly*, which performed the following calculations:

$$\text{Let initial } E_n = M_{new} \qquad (1)$$

$$\Rightarrow E_{n+1} = E_n + (M - E_n + e^*\text{Sin}(E_n)) / (1 - e^*\text{Cos}(E_n)) \qquad (2)$$

Where: M = mean anomaly (comes from true anomaly)
E = eccentric anomaly, e = eccentricity

The above Newton's Method involves repeating equation (2) until the difference between $E_{n+1}$ and $E_n$ is very small (I took a difference of 0.00001). The true anomaly $\nu$ can be worked out from the final $E_{n+1}$ using the AnomalyTo$\nu$ [21] algorithm and making sure it is in the same hemisphere as $E_{n+1}$.

Before working out the R vector of each body, of which the true anomaly is one input, I computed the total angle of each body relative to the Sun's **I** vector and compared them. Figure 7 shows the geometry:

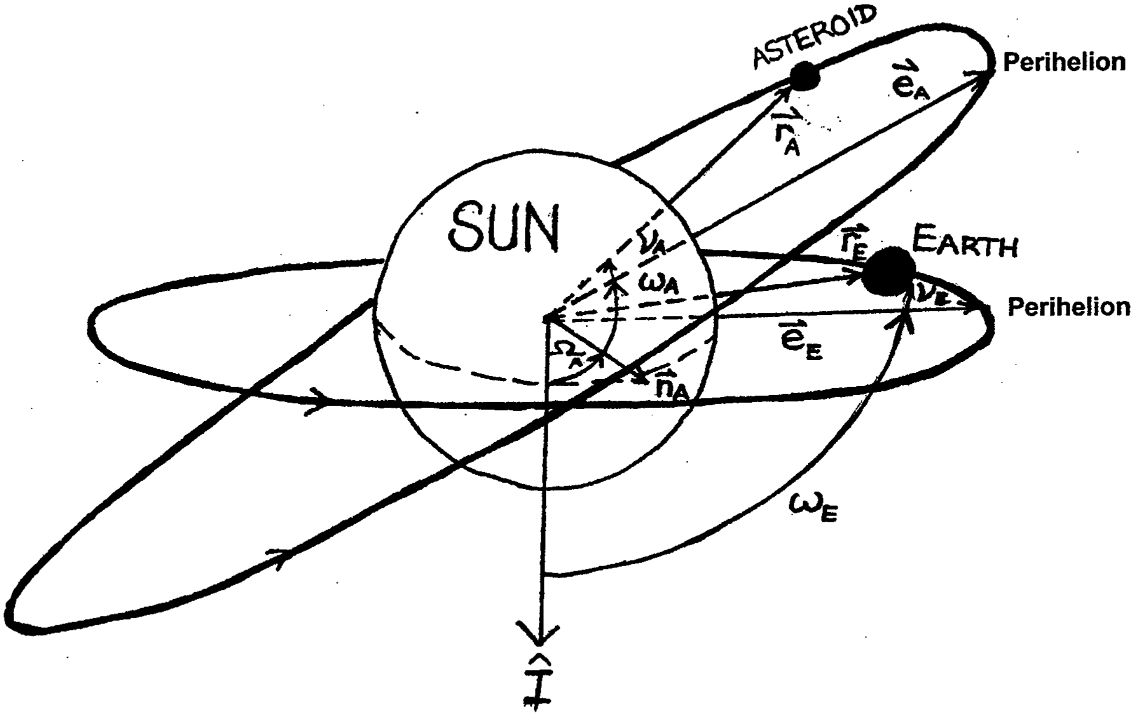


*Figure 7*

I added up the node ($\Omega$), argument of perigee ($\omega$) and true anomaly ($\nu$) for the asteroid and for the Earth at the specific time. I then took the difference between the two sums. My guess was that the closest approaches are most likely to occur when the difference between the angles is rather small. At first I was going to use angle difference as a way to weed out dates during which there was a large angle difference (greater than $90^{\circ}$). I wouldn't even bother to calculate the difference in R vectors on those days because I would expect it to be much larger than on days when the angle difference was small. Although this ought to be the case when the orbits are orientated as they are in Figure 7, it may not be true when the orbits have considerable dissimilar inclinations to the Sun, so all angle differences must be looked at. They were included in the printout of the results.

The next step after finding the true anomaly and angle difference was to work out the separate R vectors. This was accomplished using the RANDV algorithm [21], and my function *PKepler* in the program (Appendix III) includes it. It requires inputs of a, e, and $\nu$. The semiparameter must be worked out using:

$p = a(1 - e^2)$ after a has been converted to AUs.

The equations returned the R vectors in the PQW, and not IJK, frame, but it didn't matter which frame I worked in since I was only looking for the magnitude of the difference between the Rs. Finally, my *PKepler* function subtracted the elements of the two R vectors and took the result's magnitude. This was continued for each chosen JD, the M being propagated by ten days each time, or a $\Delta t$ of 864,000 seconds. The process carried on for a total time of five years, which in ten-day intervals is 183 iterations.

Since C programs can often work incorrectly, I worked out the answers by hand for a given JD and came up with the same angles and same differences in R's. To make sure the Kepler propagator was actually propagating as it should, I took Earth's orbital elements at a given JD and found out the separate elements of its R vector at that time. I then used a $\Delta t$ of 365 days (one orbit) to propagate M, and looked at the new R. It was the same, suggesting that there were no errors in the propagator.

The results, an example of which is in Appendix IV, include the magnitude of the difference in R's (called 'R'), the difference in angles and the Julian date that they occurred. The name of the asteroid in question is the name of the file at the top of the printout. For each individual asteroid, I changed the basic program. The orbital elements had to be changed for every different program, obviously. I would start by having the program print out all distances less than 1 AU. If there were none, I would rerun it at 1.5 AU, etc. If there were many at 1 AU, I would reduce the R to 0.75AU or less. I wanted about a page of output for each asteroid. At first, I was going to reduce the JD interval around a close approach to narrow the prediction down to a day, but I could tell that my results were too rough for that to serve any purpose. I could only go as accurate as ten days, if that. Appendix IV also shows how R changes cyclically with time; it goes steadily up and down as the asteroid moves away from, and then towards, the Earth.

In Table 1 are the results for the asteroids chosen by NASA to approach closely in the next five years, along with my results. As can be seen, my distances for all but a couple of the asteroids are off by a magnitude of ten. This is probably because Jupiter, with its strong gravitational pull, was not taken into account. I shall look at that later. But I predicted six of the eleven asteroids to have their closest approach within 40 days of the "true" Julian date, and 1991RB matched the JD exactly. Forty days is a fairly small interval in the total time of an asteroid's orbit.

It would have been nice to also look at the new asteroid 1997 XF11, the one in recent newspapers [13] and mentioned in the background section, but the orbital elements were not yet available.

| Asteroid | My closest determined approach (AU) | Determined JD (to the nearest 10 days) | Actual closest approach (AU) | JD | Diameter (km) |
|---|---|---|---|---|---|
| 1991 RB | 0.588 | 2451075 | 0.0401 | 2451075 | 0.6 |
| 1989 UR | 0.752 | 2451665 | 0.0800 | 2451146 | 1 |
| 1992 SK | 0.469 | 2450945 | 0.0560 | 2451264 | 1 |
| 1991 JX | 1.965 | 2452515 | 0.0500 | 2451332 | 0.8 |
| 4486 Mithra | 1.787 | 2451745 | 0.0466 | 2451771 | 3 |
| 4179 Toutatis | 0.836 | 2451825 | 0.0739 | 2451849 | 3.3 |
| 1991 VK | 0.019 | 2452315 | 0.0718 | 2452291 | 1.5 |
| 4660 Nereus | 0.094 | 2452325 | 0.029 | 2452295 | 0.8 |
| 5604 1992 FE | 0.873 | 2451595 | 0.0768 | 2452448 | 2 |
| 1991 BN | 1.438 | 2452555 | 0.0775 | 2452593 | 0.4 |
| 1990 SM | 0.419 | 2451595 | 0.0747 | 2452688 | 2 |

*Table 1* [15]

Table 2 shows the minimum angle difference over the five years for each asteroid with Earth, and its JD. There seems to be a strong correlation between the JD of the smallest angle and the NASA-predicted JD of closest approach. *Ten* of the eleven asteroid JDs now match those from NASA, seven of those exactly or within five days. But for some of these small angles I got rather large R-values. This seems to suggest that predicting how close an asteroid shall get depends more on the calculated angular difference, not the difference in Rs, at least for my method. If I used an all-inclusive program, the gravitational pull of other bodies must change the asteroid's R vector significantly, whereas the angular difference remains the same (small for close approaches, which would make sense).

| Asteroid | Least Angle Difference ($^{o}$) | JD | NASA-predicted JD of closest approach |
|---|---|---|---|
| 1991 RB | 0.802 | 2451075 | 2451075 |
| 1989 UR | 0.524 | 2451175 | 2451146 |
| 1992 SK | 0.289 | 2451275 | 2451264 |
| 1991 JX | 0.346 | 2451335 | 2451332 |
| 4486 Mithra | 1.002 | 2451775 | 2451771 |
| 4179 Toutatis | 0.326 | 2451855 | 2451849 |
| 1991 VK | 0.275 | 2452295 | 2452291 |
| 4660 Nereus | 0.373 | 2452295 | 2452295 |
| 5604 1992 FE | 0.895 | 2451885 | 2452448 |
| 1991 BN | 3.438 | 2452595 | 2452593 |
| 1990 SM | 14.500 | 2452715 | 2452688 |

*Table 2*

I also made calculations on other asteroids I randomly picked from Appendix II:

| Asteroid | Closest approach (AUs) | JD of closest approach | Least Angle Difference ($^{o}$) | JD of least angle difference |
|---|---|---|---|---|
| <u>ATENS</u> | | | | |
| 1992BF* | 0.134 | 2452085 | 64.904 | 2452605 |
| 1954XA | 0.030 | 2452095 | 74.955 | 2452725 |
| Aten | 0.093 | 2452035 | 129.689 | 2451665 |
| <u>APOLLOS</u> | | | | |
| 1988TA* | 0.180 | 2452275 | 67.762 | 2452015 |
| 1987OA | 0.767 | 2451055 | 0.468 | 2451055 |
| Orpheus* | 0.151 | 2452365 | 0.543 | 2450975 |
| Heracles | 0.307 | 2452365 | 2.733 | 2452315 |
| 1995EK1 | 0.025 | 2452375 | 42.275 | 2451115 |
| <u>AMORS</u> | | | | |
| Taranis | 0.618 | 2451205 | 68.597 | 2451055 |
| 1994AW1* | 0.671 | 2452735 | 50.173 | 2452345 |
| 1990BA | 0.929 | 2451065 | 0.032 | 2452465 |

*Table 3*

Those asteroids marked with a star (*) in Table 3 have been predicted by NASA to come within 0.1AUs of the Earth in the next 20 years. The minimum distances from Earth are probably more accurate, or at least their magnitude should be since they're not supposed to come within 0.1AUs. These asteroids may not have approached Jupiter as closely as those in Table 1 and so their orbits did not change as much. The least angle difference is in general a lot higher, and since I speculated that a small difference suggests a close approach for my method, this would be correct.

If I would have had more time, I could have included the effects of Jupiter on the asteroids' orbits and calculated how much its pull would have changed the semimajor axis and thus closest approach to Earth. I did look at the maximum acceleration possible due to Jupiter for all asteroids in Table 1. I used the equation:

$a = \mu / r^2$ , where $a$ = acceleration ($AU/TU^2$)
$\mu$ = Sun's gravitational parameter = 1 $AU^3/TU^2$
$r$ = *minimum* possible distance between the asteroid and Jupiter.

This should give me an idea of the magnitude of the acceleration at the closest approach of the asteroid and Jupiter. The closest approach was calculated by subtracting the two semimajor axes, and may actually be larger because I assumed the two bodies were in the same plane. Jupiter's semimajor axis is 5.2026 AUs. Table 4 on the next page gives results.

Also, severe changes in the minimum distance between the asteroid and Earth "occur mainly for the asteroids with revolution periods close to one-third that of Jupiter," [20] when their orbits are likely to change. Table 5 gives the periods of Jupiter and the Table 1 asteroids, as well as the fraction of Jupiter's period for each. Periods were worked out using:

$P = 2\pi\sqrt{(a^3/\mu)}$ where $P$ = the period in TUs
$a$ = the semimajor axis in AUs
$\mu$ = the Sun's gravitational parameter = 1 $AU^3/TU^2$

| Asteroid | Maximum acceleration due to Jupiter ($AU/TU^2$) |
|---|---|
| 1991 RB | 0.0710 |
| 1989 UR | 0.0588 |
| 1992 SK | 0.0640 |
| 1991 JX | 0.1389 |
| 4486 Mithra | 0.1110 |
| 4179 Toutatis | 0.1384 |
| 1991 VK | 0.0886 |
| 4660 Nereus | 0.0725 |
| 5604 1992 FE | 0.0547 |
| 1991 BN | 0.707 |
| 1990 SM | 0.1078 |

*Table 4*

| Asteroid | Period (TU) | Fraction of Jupiter's Period (TU) |
|---|---|---|
| JUPITER | 74.561 | - |
| 1991 RB | 10.973 | 0.147 |
| 1989 UR | 7.053 | 0.095 |
| 1992 SK | 8.765 | 0.118 |
| 1991 JX | 25.120 | 0.337* |
| 4486 Mithra | 20.520 | 0.275* |
| 4179 Toutatis | 25.076 | 0.336* |
| 1991 VK | 15.728 | 0.211 |
| 4660 Nereus | 11.424 | 0.153 |
| 5604 1992 FE | 5.608 | 0.075 |
| 1991 BN | 10.887 | 0.146 |
| 1990 SM | 19.901 | 0.267* |

*Table 5*

Those fractions marked with a '*' are close to one-third of Jupiter's period and so should be significantly affected by it. These results correlate with the acceleration due to Jupiter at a minimum distance – the same asteroids with periods near one-third of Jupiter's period also have higher accelerations in Table 4. The most significantly affected rocks are 1990SM, 1991JX, Mithra and Toutatis. This would explain why, in Table 1, 1991JX's JD was off by so much and its minimum distance was so large, and why 1990SM's JD was off by so much. Jupiter affects their orbits significantly, and a far better study could have been conducted if it had been included.

## Discussion of Limitations

The main limitations in this investigation are obvious: I left out major gravitational forces. Had there been more time to do so, I could have added the effects due to Jupiter and Mars, as described earlier. The effect of the moon could have been included, and even the pull of other large asteroids the asteroid in question may have passed close to. But this would have involved a program of monstrous proportions, in which all of the above mentioned orbits were propagated and the gravitational effects determined.

I assumed all orbital elements but the true anomaly remained constant over five years because the change is so small. Perhaps including the changes would have moved numbers slightly.

The list of orbital elements in Appendix II was compiled by propagating the orbits and treating Earth and moon perturbations separately. Also, every planet's perturbations were taken into account at each step and general relativistic equations of motion were used [7]. The "general relativistic advancement in the line of apsides" [7] was accounted for when the asteroid had a large eccentricity and small semimajor axis. The accuracy of the orbital elements in the given tables may not be accurate enough. Over the past 20 years there have been slight changes to all of the orbital elements as more sightings have been recorded, giving a more accurate value. So over the next few years, it may be that the orbital element values I used will change slightly.

A problem I encountered when reading about how orbits were determined by astrophysicists was that many astronomical terms were used, such as "relativistic equations of motion". These have to do with how time travel might affect an asteroid's motion, slowing it down or speeding it up. Being an engineer, I had little understanding of such concepts, let alone how to calculate them. It was mentioned that using 'nonrelativistic equations' of motion (which I did) would introduce a significant error.

I looked at only a sample of asteroids, and they were non-randomly picked. I used asteroids that had already been predicted to come close to Earth so I might check if I achieved the same results as NASA. The others I chose because I knew they *weren't* supposed to come close ("close" being within 0.1 AUs of the Earth).

I had plans to narrow the time interval, to get the day of closest approach, rather than the nearest 10 days. But my answers are so rough anyway that there seemed to be little point in narrowing down the time; the answer would just be very inaccurate. Of course, the NASA reference close approaches I used could be slightly wrong too, due to inaccuracy in the orbital elements or some factor being left out of the equations.

Finally, errors may have occurred if I mistyped the orbital elements into the program.

## Discussion of Applications

The simple method I used can give a rough estimate of which asteroids might come closest to Earth and when. The key seemed to be looking at the minimum angle difference to find the time interval a closest approach may occur. The program is *not* accurate for predicting the distance of nearest approach.

A use for my program would be to find all times that the smallest angle difference is less than 15°. Then a more advanced program that takes longer and considers all other gravitational forces can use my time intervals to find a more accurate distance and time. This would save time because the more complicated program would not have to go through every possible date.

Not only could a program that works properly be used to predict collisions of asteroids with Earth, but also it could predict when they come close enough to Earth for us to be able to set up a rendezvous with them. A spacecraft could approach them to take photos or, in the future, perhaps we could mine the asteroids for their valuable minerals.

## Conclusion

My investigation showed that it is not all that useful to only use Kepler's algorithm to predict how close asteroids may come to Earth. Using Kepler's algorithm, close approaches are quite inaccurate. However, it is possible to predict when they may be nearest, within 50 days or so. This is accomplished by looking at the angular difference between the asteroid and the Earth. If it is quite small (less than $15^{\circ}$), a close approach is likely. I would need to test this hypothesis on many more asteroids before I could be sure that it is true. For now, I would say that my program could give a rough estimate of the time period, thus narrowing down the dates to look at with a more advanced program. Including the gravitational effects of Jupiter may have improved my results dramatically.

# Bibliography

1. Barnes-Svarney, Patricia, "Introduction," Asteroid. Earth Destroyer or New Frontier?, Plenum Press, New York, 1996, pp.1-7.
2. *http://www.d91.k12.id.us/www/skyline/student_projects/science/landon/ast.htm*
3. Barnes-Svarney, Patricia, "The Planet That Never Was?," Asteroid. Earth Destroyer or New Frontier?, Plenum Press, New York, 1996, pp.42-55.
4. *http://www.eecs.wsu.edu/~hudson/Toutatis/press.html*
5. Erickson, John, "Meteors and Comets," Target Earth! Asteroid Collisions Past & Future, Tab Books, Blue Ridge Summit, PA, 1991, pp.118 – 131.
6. Barnes-Svarney, Patricia, "Noticing Near-Earthers," Asteroid. Earth Destroyer or New Frontier?, Plenum Press, New York, 1996, pp.210-222.
7. Ahrens, Thomas J., and Harris, Alan W., "Deflection and fragmentation of near-Earth asteroids," *Nature*, Vol. 360, December 1992, pp. 429.
8. Chapman, Clark R., and Morrison, David, "Impacts on the Earth by asteroids and comets: assessing the hazard," *Nature*, Vol. 367, January 1994, pp. 33 - 34.
9. Steel, Duncan, "The Swarm Around Us," Rogue Asteroids And Doomsday Comets, John Wiley & Sons, Inc., New York, 1995, pp. 15-38.
10. Rabinowitz, D.L., Gehreis, T., Scotti, J.V., McMillan, R.S., Perry, M.L., Wisniewski,W., Larson, S.M., Howell, E.S., and Mueller, B.E.A., "Evidence for a near-Earth asteroid belt," *Nature*, Vol. 363, June 1993, pp. 704-706.
11. Barnes-Svarney, Patricia, "The Hunt And The Hunted," Asteroid. Earth Destroyer or New Frontier?, Plenum Press, New York, 1996, pp.242-259.

12. Verschuur, Gerrit L., "On the Edge of Extinction," Imact! The Threat of Comets And Asteroids, Oxford University Press, Oxford, 1996, pp. 108 – 119.
13. The Boston Globe, "Asteroid zooms toward ground zero : Earth," *The Gazette*, Vol. 126, Number 354, 12 March, 1998, pp.1.
14. Yeomans, D.K., and Chodas, P.W., "Predicting Close Approaches of Asteroids And Comets to Earth," Hazards Due To Comets And Asteroids, 1st ed., University of Arizona Press, Tuscon, 1994, pp. 241 – 281.
15. *http://ccf.arc.nasa.gov/sst/close.html*
16. Steel, Duncan, "Catastrophic Scenarios," Rogue Asteroids And Doomsday Comets, John Wiley & Sons, Inc., New York, 1995, pp. 39-54.
17. Bowell, Edward, and Muinonen, Karri, "NEO Groundbased Search Strategies," Hazards Due To Comets And Asteroids, 1st ed., University of Arizona Press, Tucson, 1994, pp. 149 – 151.
18. Rabinowitz, D., Bowell, E., Shoemaker, E., and Muinonen, K, "The Population of Earth-Crossing Asteroids," Hazards Due To Comets And Asteroids, 1st ed., University of Arizona Press, Tuscon, 1994, pp. 241 – 281.
19. Steel, Duncan, "Showdown at Los Alamos," Rogue Asteroids And Doomsday Comets, John Wiley & Sons, Inc., New York, 1995, pp. 221-240.
20. *http://cfa-www.harvard.edu/iau/pressreleases/100PHAs.html*
21. Steel, Duncan, "The World on Fire," Rogue Asteroids And Doomsday Comets, John Wiley & Sons, Inc., New York, 1995, pp. 55-74.
22. Vallado, David A., Fundamentals of Astrodynamics and Applications, McGraw-Hill Companies, Inc., New York, 1997.

# Appendix I

*NASA Ames Space Science Division*

---

# Predicted Close Approaches

The following are some of the predicted close asteroid and comet approaches through the year 2020, supplied by Don Yeomans of the NASA/Caltech Jet Propulsion Laboratory.

**NOTE:** CA = closest approach distance to the Earth in Astronomical Units (150 million km)

## Comets and asteroids passing within 0.1 AU of the Earth through 2020

| Object | Date (TBD) | CA Distance | Absolute Magnitude | RA | DEC |
|---|---|---|---|---|---|
| 1991 JX | 1995 06 9.098 | .0341 | 18.5 | 278 | 37 |
| 2063 Bacchus | 1996 03 31.670 | .0678 | 16.4 | 230 | 59 |
| 1991 CS | 1996 08 28.419 | .0620 | 17.5 | 53 | -2 |
| 4197 1982 TA | 1996 10 25.639 | .0846 | 14.5 | 289 | 72 |
| 3908 1980 PA | 1996 10 27.860 | .0613 | 17.4 | 2 | 32 |
| 1991 VE | 1996 10 29.543 | .0853 | 19.0 | 296 | -66 |
| 4179 Toutatis | 1996 11 29.953 | .0354 | 15.4 | 204 | -22 |
| 1991 VK | 1997 01 10.695 | .0749 | 17.0 | 287 | -18 |
| 6037 1988 EG | 1998 02 28.914 | .0318 | 18.7 | 77 | -28 |
| 1991 RB | 1998 09 18.475 | .0401 | 19.0 | 170 | -46 |
| 1989 UR | 1998 11 28.689 | .0800 | 18.0 | 4 | -18 |
| 1992 SK | 1999 03 26.265 | .0560 | 17.5 | 28 | 41 |
| 1991 JX | 1999 06 2.819 | .0500 | 18.5 | 291 | 12 |
| 4486 Mithra | 2000 08 14.365 | .0466 | 15.4 | 112 | -69 |
| 4179 Toutatis | 2000 10 31.186 | .0739 | 15.4 | 218 | -21 |
| 1991 VK | 2002 01 16.498 | .0718 | 17.0 | 289 | -24 |
| 4660 Nereus | 2002 01 22.512 | .0290 | 18.3 | 287 | -13 |
| 5604 1992 FE | 2002 06 22.264 | .0768 | 17.0 | 157 | -47 |
| 1991 BN | 2002 11 14.726 | .0775 | 20.0 | 325 | 19 |
| 1990 SM | 2003 02 17.275 | .0747 | 16.5 | 59 | 40 |
| 1991 JX | 2003 05 20.681 | .0922 | 18.5 | 301 | -6 |
| 1990 OS | 2003 11 11.448 | .0250 | 20.0 | 194 | 40 |
| 1989 QF | 2004 02 4.267 | .0748 | 18.0 | 22 | 42 |
| 4179 Toutatis | 2004 09 29.567 | .0104 | 15.4 | 218 | -60 |
| 1988 XB | 2004 11 21.965 | .0728 | 17.5 | 164 | -1 |
| 1992 BF | 2005 03 3.695 | .0630 | 19.0 | 129 | -62 |
| 1993 VW | 2005 04 24.904 | .0862 | 16.5 | 137 | -24 |
| 1992 UY4 | 2005 08 8.424 | .0402 | 17.5 | 359 | 12 |

# Appendix II

Catalogue of Near Earth Asteroids: orbits of known Atens/Apollos/Amors as of 1995 March 21. Semimajor axes (a) are in astronomical units, angles are in degrees, and estimated diameters are in kilometers. The final column gives the spectral type if available. Data supplied by David Tholen of the University of Hawaii.

TABLE 1: ATENS

| | Desig | a | e | i | Node | Peri | M | Epoch | Diam | Type |
|---|---|---|---|---|---|---|---|---|---|---|
| 2062 Aten | 1976 AA | 0.9666 | 0.1826 | 18.93 | 107.99 | 147.82 | 299.11 | 2449800.5 | 1 | S |
| 2100 Ra-Shalom | 1978 RA | 0.8320 | 0.4365 | 15.75 | 170.24 | 355.95 | 104.33 | 2449800.5 | 4 | C |
| 2340 Hathor | 1976 UA | 0.8438 | 0.4499 | 5.85 | 210.93 | 39.83 | 3.31 | 2449800.5 | 0.5 | CSU |
| 3362 Khufu | 1984 QA | 0.9894 | 0.4686 | 9.91 | 151.97 | 54.84 | 345.56 | 2449800.5 | 1 | |
| 3554 Amun | 1986 EB | 0.9737 | 0.2804 | 23.35 | 358.01 | 359.34 | 308.42 | 2449800.5 | 3 | |
| 3753 | 1986 TO | 0.9977 | 0.5147 | 19.81 | 125.70 | 43.62 | 67.79 | 2449800.5 | 5 | |
| 5381 Sekhmet | 1991 JY | 0.9474 | 0.2959 | 48.97 | 57.88 | 37.41 | 177.08 | 2449800.5 | 2 | |
| 5590 | 1990 VA | 0.9853 | 0.2793 | 14.19 | 215.72 | 34.35 | 305.83 | 2449800.5 | 0.4 | |
| 5604 | 1992 FE | 0.9270 | 0.4054 | 4.78 | 311.43 | 82.36 | 234.57 | 2449800.5 | 2 | |
| | 1995 CR | 0.9057 | 0.8678 | 4.00 | 342.33 | 322.10 | 345.03 | 2449800.5 | 0.2 | |
| | 1994 XL1 | 0.6708 | 0.5263 | 28.19 | 252.02 | 356.49 | 27.61 | 2449800.5 | 0.3 | |
| | 1994 WR12 | 0.7540 | 0.4053 | 7.06 | 62.41 | 205.59 | 305.39 | 2449800.5 | 0.2 | |
| | 1994 TF2 | 0.9932 | 0.2836 | 23.75 | 174.64 | 349.62 | 29.72 | 2449800.5 | 0.6 | |
| | 1994 GL | 0.6844 | 0.5019 | 3.64 | 196.46 | 179.06 | 69.10 | 2449800.5 | 0.06 | |
| | 1993 VD | 0.8766 | 0.5493 | 2.05 | 2.25 | 253.51 | 348.33 | 2449800.5 | 0.2 | |
| | 1993 DA | 0.9353 | 0.0937 | 12.40 | 328.53 | 353.96 | 300.17 | 2449800.5 | 0.02 | |
| | 1992 BF | 0.9079 | 0.2710 | 7.25 | 314.94 | 336.28 | 82.03 | 2449800.5 | 0.6 | |
| | 1991 VE | 0.8905 | 0.6638 | 7.20 | 61.49 | 193.33 | 93.67 | 2449800.5 | 0.6 | |
| | 1989 VA | 0.7286 | 0.5947 | 28.79 | 224.95 | 2.79 | 42.66 | 2449800.5 | 1 | |
| | 1989 UQ | 0.9152 | 0.2649 | 1.28 | 178.03 | 14.62 | 272.91 | 2449800.5 | 0.6 | |
| | 1954 XA | 0.7775 | 0.3451 | 3.91 | 188.77 | 58.73 | 120.76 | 2449800.5 | 0.6 | |

Catalogue of Near Earth Asteroids: orbits of known Atens/Apollos/Amors as of 1995 March 21. Semimajor axes (a) are in astronomical units, angles are in degrees, and estimated diameters are in kilometers. The final column gives the spectral type if available. Data supplied by David Tholen of the University of Hawaii.

TABLE 2: APOLLOS

| | Desig | a | e | i | Node | Peri | M | Epoch | Diam | Type |
|---|---|---|---|---|---|---|---|---|---|---|
| 1566 Icarus | 1949 MA | 1.0780 | 0.8267 | 22.88 | 87.47 | 31.20 | 10.06 | 2449800.5 | 2 | |
| 1620 Geographos | 1951 RA | 1.2455 | 0.3354 | 13.33 | 336.65 | 276.74 | 191.54 | 2449800.5 | 2.3 | S |
| 1685 Toro | 1948 OA | 1.3670 | 0.4360 | 9.37 | 273.70 | 126.95 | 18.24 | 2449800.5 | 12 | S |
| 1862 Apollo | 1932 HA | 1.4711 | 0.5598 | 6.35 | 35.27 | 285.58 | 44.34 | 2449800.5 | 1.5 | Q |
| 1863 Antinous | 1948 EA | 2.2600 | 0.6062 | 18.41 | 346.84 | 266.91 | 280.57 | 2449800.5 | 2 | SU |
| 1864 Daedalus | 1971 FA | 1.4609 | 0.6146 | 22.17 | 6.09 | 325.43 | 126.42 | 2449800.5 | 3 | SQ |
| 1865 Cerberus | 1971 UA | 1.0801 | 0.4669 | 16.09 | 212.35 | 325.13 | 204.71 | 2449800.5 | 1 | S |
| 1866 Sisyphus | 1972 XA | 1.8933 | 0.5391 | 41.16 | 63.01 | 292.97 | 224.27 | 2449800.5 | 9.6 | |
| 1981 Midas | 1973 EA | 1.7761 | 0.6500 | 39.83 | 356.48 | 267.68 | 81.87 | 2449800.5 | 4 | |
| 2063 Bacchus | 1977 HB | 1.0779 | 0.3495 | 9.41 | 32.63 | 55.05 | 92.76 | 2449800.5 | 2 | |
| 2101 Adonis | 1936 CA | 1.8738 | 0.7648 | 1.34 | 350.02 | 42.30 | 42.70 | 2449800.5 | 0.7 | |
| 2102 Tantalus | 1975 YA | 1.2901 | 0.2985 | 64.01 | 93.70 | 61.60 | 13.25 | 2449800.5 | 3.3 | |
| 2135 Aristaeus | 1977 HA | 1.5997 | 0.5031 | 23.04 | 190.74 | 290.63 | 341.09 | 2449800.5 | 1 | |
| 2201 Oljato | 1947 XC | 2.1759 | 0.7106 | 2.51 | 76.34 | 95.81 | 254.33 | 2449800.5 | 2 | |
| 2212 Hephaistos | 1978 SB | 2.1681 | 0.8335 | 11.77 | 27.75 | 208.36 | 82.17 | 2449800.5 | 5 | SG |
| 2329 Orthos | 1976 WA | 2.4024 | 0.6587 | 24.41 | 168.84 | 145.75 | 352.75 | 2449800.5 | 4 | |
| 3103 Eger | 1982 BB | 1.4060 | 0.3546 | 20.93 | 129.22 | 253.79 | 31.51 | 2449800.5 | 3 | |
| 3200 Phaethon | 1983 TB | 1.2713 | 0.8901 | 22.10 | 264.87 | 321.83 | 23.14 | 2449800.5 | 5.2 | F |
| 3360 | 1981 VA | 2.4645 | 0.7430 | 21.74 | 244.81 | 60.58 | 183.33 | 2449800.5 | 2 | |
| 3361 Orpheus | 1982 HR | 1.2091 | 0.3225 | 2.68 | 189.11 | 301.53 | 303.54 | 2449800.5 | 0.6 | |
| 3671 Dionysus | 1984 KD | 2.1952 | 0.5429 | 13.62 | 81.76 | 203.63 | 105.31 | 2449800.5 | 2 | |
| 3752 Camillo | 1985 PA | 1.4136 | 0.3023 | 55.54 | 147.33 | 312.21 | 154.91 | 2449800.5 | 3 | |
| 3757 | 1982 XB | 1.8350 | 0.4465 | 3.87 | 74.50 | 16.77 | 331.11 | 2449800.5 | 0.5 | S |
| 3838 Epona | 1986 WA | 1.5047 | 0.7018 | 29.28 | 235.06 | 49.43 | 219.51 | 2449800.5 | 3 | |
| 4015 Wilson-Harrington | 1979 VA | 2.6418 | 0.6219 | 2.78 | 270.14 | 91.07 | 216.92 | 2449800.5 | 4 | CF |
| 4034 | 1986 PA | 1.0599 | 0.4441 | 11.17 | 157.44 | 296.44 | 222.07 | 2449800.5 | 1 | |
| 4179 Toutatis | 1989 AC | 2.5154 | 0.6361 | 0.47 | 128.30 | 274.08 | 212.59 | 2449800.5 | 3.3 | |
| 4183 Cuno | 1959 LM | 1.9809 | 0.6369 | 6.76 | 295.17 | 235.22 | 321.88 | 2449800.5 | 5 | |
| 4197 | 1982 TA | 2.2972 | 0.7727 | 12.20 | 9.50 | 119.23 | 182.29 | 2449800.5 | 5 | |
| 4257 Ubasti | 1987 QA | 1.6471 | 0.4684 | 40.70 | 168.65 | 278.89 | 165.20 | 2449800.5 | 2 | |
| 4341 Poseidon | 1987 KF | 1.8357 | 0.6787 | 11.86 | 107.55 | 15.47 | 83.01 | 2449800.5 | 3 | |
| 4450 Pan | 1987 SY | 1.4418 | 0.5865 | 5.51 | 311.52 | 291.38 | 165.58 | 2449800.5 | 1.5 | |
| 4486 Mithra | 1987 SB | 2.2012 | 0.6626 | 3.04 | 81.94 | 168.47 | 138.47 | 2449800.5 | 3 | |
| 4544 Xanthus | 1989 FB | 1.0420 | 0.2502 | 14.14 | 23.44 | 333.62 | 66.04 | 2449800.5 | 1.5 | |
| 4581 Asclepius | 1989 FC | 1.0226 | 0.3571 | 4.91 | 179.85 | 255.00 | 354.62 | 2449800.5 | 0.3 | |
| 4660 Nereus | 1982 DB | 1.4897 | 0.3602 | 1.41 | 313.97 | 157.96 | 91.02 | 2449800.5 | 0.8 | |
| 4769 Castalia | 1989 PB | 1.0631 | 0.4832 | 8.88 | 325.04 | 121.22 | 334.57 | 2449800.5 | 1.6 | |
| 4953 | 1990 MU | 1.6208 | 0.6569 | 24.42 | 77.42 | 77.38 | 167.94 | 2449800.5 | 5 | |
| 5011 Ptah | 6743 P-L | 1.6350 | 0.4999 | 7.39 | 10.38 | 105.36 | 124.94 | 2449800.5 | 1.5 | |
| 5131 | 1990 BG | 1.4866 | 0.5700 | 36.38 | 109.83 | 135.69 | 242.65 | 2449800.5 | 6 | |
| 5143 Heracles | 1991 VL | 1.8338 | 0.7713 | 9.18 | 310.04 | 226.39 | 78.41 | 2449800.5 | 6 | |
| 5189 | 1990 UQ | 1.5508 | 0.4778 | 3.58 | 134.80 | 159.37 | 148.71 | 2449800.5 | 1 | |
| 5496 | 1973 NA | 2.4337 | 0.6382 | 68.02 | 100.38 | 118.24 | 272.29 | 2449800.5 | 4 | |
| 5645 | 1990 SP | 1.3548 | 0.3874 | 13.51 | 45.23 | 47.96 | 255.08 | 2449800.5 | 2 | |
| 5660 | 1974 MA | 1.7861 | 0.7628 | 37.94 | 301.85 | 126.71 | 216.91 | 2449800.5 | 3 | |
| 5693 | 1993 EA | 1.2721 | 0.5853 | 5.05 | 96.60 | 258.56 | 336.98 | 2449800.5 | 1.5 | |
| 5731 | 1988 VP4 | 2.2632 | 0.6526 | 11.64 | 282.06 | 215.63 | 283.48 | 2449800.5 | 3 | |
| 5786 Talos | 1991 RC | 1.0814 | 0.8267 | 23.24 | 160.67 | 8.26 | 173.14 | 2449800.5 | 2 | |
| 5828 | 1991 AM | 1.6977 | 0.6957 | 30.04 | 124.91 | 152.53 | 285.71 | 2449800.5 | 2 | |
| 6037 | 1988 EG | 1.2690 | 0.4994 | 3.48 | 182.27 | 241.46 | 18.74 | 2449800.5 | 0.7 | |
| 6047 | 1991 TB1 | 1.4537 | 0.3521 | 23.46 | 5.57 | 103.55 | 292.54 | 2449800.5 | 1.5 | |
| 6053 | 1993 BW3 | 2.1474 | 0.5288 | 21.59 | 317.96 | 74.57 | 298.72 | 2449800.5 | 5 | |
| 6063 | 1984 KB | 2.2157 | 0.7643 | 4.85 | 169.25 | 336.49 | 113.98 | 2449800.5 | 4 | |
| 6239 | 1989 QF | 1.1513 | 0.4127 | 3.93 | 344.15 | 239.50 | 250.24 | 2449800.5 | 0.9 | |
| | 1995 EK1 | 2.2509 | 0.7746 | 8.81 | 355.03 | 296.53 | 342.08 | 2449800.5 | 1 | |
| | 1995 DW1 | 1.0405 | 0.4380 | 15.10 | 348.26 | 326.88 | 265.09 | 2449800.5 | 0.2 | |
| | 1995 DV1 | 3.1257 | 0.6915 | 3.69 | 171.63 | 283.97 | 14.05 | 2449800.5 | 0.07 | |
| | 1995 CS | 1.9400 | 0.7753 | 2.61 | 135.06 | 252.05 | 34.39 | 2449800.5 | 0.04 | |
| | 1995 BL2 | 1.2315 | 0.4943 | 23.08 | 311.72 | 348.22 | 252.60 | 2449800.5 | 1 | |
| | 1994 XM1 | 2.0884 | 0.5688 | 4.11 | 76.35 | 40.66 | 24.37 | 2449800.5 | 0.01 | |
| | 1994 XG | 1.5719 | 0.4900 | 11.32 | 231.10 | 46.14 | 157.53 | 2449800.5 | 1 | |
| | 1994 XD | 2.3590 | 0.7291 | 4.34 | 96.96 | 247.73 | 48.66 | 2449800.5 | 0.6 | |
| | 1994 VH8 | 1.6355 | 0.4428 | 3.37 | 37.78 | 314.14 | 84.29 | 2449800.5 | 0.01 | |
| | 1994 UG | 1.2258 | 0.2457 | 4.49 | 11.73 | 225.91 | 247.95 | 2449800.5 | 0.2 | |
| | 1994 RC | 2.2678 | 0.6018 | 4.72 | 345.45 | 284.34 | 75.84 | 2449800.5 | 0.6 | |
| | 1994 RB | 2.4883 | 0.6394 | 26.62 | 338.94 | 52.47 | 41.21 | 2449800.5 | 0.1 | |
| | 1994 PC1 | 1.3457 | 0.3277 | 33.50 | 117.29 | 47.53 | 273.04 | 2449800.5 | 2 | |
| | 1994 PM | 1.4775 | 0.7523 | 17.94 | 139.38 | 303.27 | 92.69 | 2449800.5 | 1 | |
| | 1994 NE | 2.0360 | 0.6045 | 27.53 | 104.29 | 246.20 | 72.70 | 2449800.5 | 0.4 | |
| | 1994 LX | 1.2614 | 0.3464 | 36.90 | 110.65 | 349.01 | 24.35 | 2449800.5 | 4 | |
| | 1994 GV | 2.0300 | 0.5228 | 0.45 | 19.31 | 154.30 | 125.40 | 2449800.5 | 0.01 | |

```
1994 GK    1.9609 0.6064  5.66  14.67 111.58 142.34  2449800.5  0.06
1994 FA    1.7358 0.4157 13.04 355.09 154.66 170.31  2449800.5  0.04
1994 ES1   1.4117 0.5897  0.94 352.34 279.11 188.61  2449800.5  0.008
1994 EU    1.3725 0.2749  6.44 350.96 145.77 250.26  2449800.5  0.03
1994 EK    1.9992 0.6067  5.76 333.54  98.01 159.90  2449800.5  0.4
1994 CN2   1.5732 0.3949  1.43  98.93 247.89 345.40  2449800.5  2
1994 CK1   1.8977 0.6200  4.40 328.11  27.67 247.78  2449800.5  1.5
1994 CJ1   1.4908 0.3258  2.31 171.61  64.92 161.22  2449800.5  0.2
1994 CC    1.6370 0.4169  4.63 268.11  24.63  63.62  2449800.5  1
1994 CB    1.1491 0.1450 18.25 310.04 288.40 242.82  2449800.5  0.2
1994 AH2   2.5255 0.7114  9.63 163.68  24.82  80.74  2449800.5  2
1993 XN2   2.1173 0.5356 25.38  59.06 312.89 172.33  2449800.5  2
1993 WD    1.0066 0.2666 63.46  55.89 132.30  10.01  2449800.5  2
1993 VW    1.6949 0.4843  8.68 230.58 280.93 174.42  2449800.5  2
1993 VB    1.9098 0.5197  5.06 145.23 322.63 164.63  2449800.5  0.5
1993 VA    1.3559 0.3912  7.26 132.60 336.35 281.97  2449800.5  1.5
1993 UC    2.4380 0.6626 25.99 165.41 322.95 103.06  2449800.5  3
1993 UA    2.0201 0.5244  4.58  26.48 330.11 186.57  2449800.5  0.04
1993 TZ    2.0235 0.5633  4.16 202.96 231.23 166.07  2449800.5  0.02
1993 QA    1.4767 0.3161 12.63 146.09 323.25 198.77  2449800.5  1
1993 PC    1.1543 0.4743  4.15 336.85 168.12 289.61  2449800.5  1
1993 PB    1.4232 0.6064 40.84 315.32 212.21  79.63  2449800.5  2
1993 KA2   2.2273 0.7745  3.18 238.78 261.44 213.05  2449800.5  0.006
1993 KH    1.2338 0.3110 12.80  53.86 293.57  46.54  2449800.5  0.6
1993 KA    1.2552 0.1974  6.05 235.17 341.90 125.65  2449800.5  0.02
1993 HP1   1.9915 0.5104  8.00  36.37 152.25 251.92  2449800.5  0.02
1993 HD    1.4322 0.6633  5.74 201.77 252.55  78.03  2449800.5  0.1
1993 HC    1.9888 0.5069  9.39 200.85 306.32 266.26  2449800.5  0.3
1993 GD    1.1022 0.2380 15.45 200.87 201.92  24.57  2449800.5  0.3
1993 FA1   1.4262 0.2886 20.46 186.67 343.60  68.99  2449800.5  0.03
1993 BX3   1.3953 0.2809  2.79 174.99 289.77 123.00  2449800.5  0.3
1993 BW2   1.3352 0.3061 21.91 120.50 287.37 185.43  2449800.5  1
1992 YD3   1.1661 0.1372 27.04 273.63 173.75 284.16  2449800.5  0.02
1992 UY4   2.6543 0.6198  2.83 308.41  37.43 211.13  2449800.5  1
1992 TB    1.3418 0.4622 28.31 185.02   5.92   5.91  2449800.5  1
1992 SY    2.2087 0.5503  8.02   5.62 114.98 221.63  2449800.5  1
1992 SK    1.2485 0.3249 15.31   8.36 233.48  14.91  2449800.5  1
1992 QN    1.1908 0.3593  9.58 355.40 202.11  92.97  2449800.5  2
1992 LC    2.5193 0.7049 17.84  61.28  89.64 267.31  2449800.5  4
1992 JD    1.0347 0.0316 13.54 221.92 285.87 338.93  2449800.5  0.03
1992 JB    1.5564 0.3598 16.07 217.81 306.75 203.71  2449800.5  1
1992 HF    1.3907 0.5617 13.30 212.91 128.05 219.90  2449800.5  0.3
1992 HE    2.2402 0.5722 37.36  26.62 262.57 295.62  2449800.5  6
1992 DU    1.1598 0.1748 25.05 337.28 121.63 207.37  2449800.5  0.04
1992 CC1   1.3914 0.3749 36.88 348.61  21.90  70.72  2449800.5  4
1992 BC    1.4135 0.3484 14.21 122.82  77.07 277.34  2449800.5  0.6
1991 XA    2.2690 0.5704  5.28  76.17 309.11 357.59  2449800.5  0.06
1991 WA    1.5752 0.6425 39.65  66.07 241.73 275.36  2449800.5  2
1991 VK    1.8436 0.5059  5.41 294.37 173.25 101.30  2449800.5  1.5
1991 VH    1.1363 0.1437 13.91 138.82 206.99 320.12  2449800.5  1.5
1991 VG    1.0269 0.0491  1.44  73.51  24.15  38.74  2449800.5  0.007
1991 VA    1.4288 0.3516  6.52  36.97 313.41  17.16  2449800.5  0.02
1991 TF3   2.0414 0.5303 14.04   6.02 303.20  86.12  2449800.5  0.6
1991 TB2   2.3977 0.8352  8.62 296.41 195.66 317.29  2449800.5  1.5
1991 TU    1.4068 0.3306  7.55 192.73 222.09   5.56  2449800.5  0.008
1991 TT    1.1929 0.1605 14.75 191.77 218.11 209.31  2449800.5  0.02
1991 RB    1.4502 0.4839 19.53 358.88  68.71 333.61  2449800.5  0.6
1991 LH    1.3520 0.7305 52.06 280.16 203.92 253.90  2449800.5  1.5
1991 JX    2.5190 0.5990  2.31 212.16  64.47 337.11  2449800.5  0.8
1991 JW    1.0383 0.1183  8.71  53.41 301.76 116.55  2449800.5  0.5
1991 GO    1.9594 0.6618  9.66  24.30  88.58 177.46  2449800.5  0.6
1991 EE    2.2460 0.6244  9.76 168.46 115.03  30.78  2449800.5  1
1991 DG    1.4271 0.3629 11.15 179.63  63.05  89.94  2449800.5  0.6
1991 CB1   1.6870 0.5946 14.56 316.85 345.53 191.78  2449800.5  1
1991 CS    1.1229 0.1646 37.10 156.23 249.26 235.76  2449800.5  1
1991 BN    1.4426 0.3979  3.44 268.46  80.54 237.31  2449800.5  0.4
1991 BB    1.1863 0.2725 38.47 294.34 322.81 333.44  2449800.5  2
1991 BA    2.1652 0.6734  2.12 118.25  71.86  98.58  2449800.5  0.008
1991 AQ    2.2210 0.7771  3.21 342.06 239.69  78.62  2449800.5  1.5
1990 UO    1.2341 0.7582 29.34 205.06 332.95   7.23  2449800.5  0.3
1990 UN    1.7093 0.5277  3.66   7.62  97.08 325.95  2449800.5  0.08
1990 UA    1.7212 0.5519  0.96 102.09 203.87   9.71  2449800.5  0.5
1990 TG1   2.4849 0.6929  9.06 204.37  33.28 114.25  2449800.5  4
1990 SS    1.7029 0.4748 19.39 359.43 115.74 310.26  2449800.5  0.6
1990 SM    2.1567 0.7754 11.56 137.28 105.91 168.03  2449800.5  2
1990 OS    1.6691 0.4590  1.10 347.40  20.03  33.69  2449800.5  0.4
1990 MF    1.7468 0.4556  1.86 209.87 113.89   0.37  2449800.5  0.8
1990 HA    2.5777 0.6932  3.88 184.43 307.89  80.94  2449800.5  1.5
1989 VB    1.8648 0.4608  2.13  38.34 329.60  51.13  2449800.5  0.4
1989 UR    1.0801 0.3563 10.34 233.89 289.29 198.37  2449800.5  1
```

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1989 UP | 1.8637 | 0.4732 | 3.86 | 52.79 | 17.21 | 33.00 | 2449800.5 | 0.3 | |
| | 1989 JA | 1.7704 | 0.4841 | 15.23 | 60.93 | 231.80 | 152.06 | 2449800.5 | 1.5 | |
| | 1989 DA | 2.1623 | 0.5433 | 6.44 | 349.08 | 138.73 | 334.08 | 2449800.5 | 1 | |
| | 1989 AZ | 1.6457 | 0.4682 | 11.76 | 295.06 | 111.63 | 1.15 | 2449800.5 | 0.5 | |
| | 1988 XB | 1.4674 | 0.4816 | 3.12 | 73.02 | 279.79 | 228.74 | 2449800.5 | 1 | |
| | 1988 TA | 1.5408 | 0.4786 | 2.54 | 194.49 | 104.57 | 163.78 | 2449800.5 | 0.2 | |
| | 1987 OA | 1.4962 | 0.5956 | 9.02 | 179.69 | 235.38 | 22.98 | 2449800.5 | 0.8 | |
| | 1986 JK | 2.7960 | 0.6806 | 2.13 | 62.17 | 232.40 | 311.67 | 2449800.5 | 0.6 | |
| | 1984 QY1 | 3.5976 | 0.9390 | 17.85 | 144.72 | 335.79 | 188.67 | 2449800.5 | 11 | |
| | 1983 VB | 1.8189 | 0.4752 | 12.05 | 247.70 | 115.36 | 244.46 | 2449800.5 | 0.8 | |
| | 1983 VA | 2.6106 | 0.6926 | 16.24 | 76.81 | 11.67 | 240.77 | 2449800.5 | 2 | |
| | 1983 LC | 2.6304 | 0.7089 | 1.52 | 159.07 | 184.67 | 259.64 | 2449800.5 | 0.6 | |
| | 1979 XB | 2.2622 | 0.7141 | 24.85 | 85.14 | 75.64 | 162.17 | 2449800.5 | 0.6 | |
| | 1978 CA | 1.1246 | 0.2148 | 26.11 | 160.63 | 102.12 | 30.27 | 2449800.5 | 1 | S |
| | 1950 DA | 1.6840 | 0.5023 | 12.08 | 356.28 | 224.26 | 203.55 | 2449800.5 | 3 | |
| Hermes | 1937 UB | 1.6463 | 0.6236 | 6.13 | 34.11 | 91.85 | 27.19 | 2449800.5 | 1 | |
| | 6344 P-L | 2.6270 | 0.6309 | 4.47 | 180.50 | 237.09 | 30.16 | 2449800.5 | 0.2 | |
| | 5025 P-L | 4.2089 | 0.8947 | 6.34 | 354.67 | 151.44 | 341.82 | 2449800.5 | 5 | |

---

Go to: Near Earth Asteroids

Catalogue of Near Earth Asteroids: orbits of known Atens/Apollos/Amors as of 1995 March 21. Semimajor axes (a) are in astronomical units, angles are in degrees, and estimated diameters are in kilometers. The final column gives the spectral type if available. Data supplied by David Tholen of the University of Hawaii.

TABLE 3: AMORS

| | Desig | a | e | i | Node | Peri | M | Epoch | Diam | Type |
|---|---|---|---|---|---|---|---|---|---|---|
| 433 Eros | | 1.4582 | 0.2229 | 10.82 | 303.71 | 178.60 | 161.38 | 2449800.5 | 20. | S |
| 719 Albert | | 2.5840 | 0.5393 | 11.24 | 183.96 | 155.07 | 42.87 | 2449800.5 | 2 | |
| 887 Alinda | | 2.4928 | 0.5594 | 9.27 | 110.09 | 349.81 | 136.26 | 2449800.5 | 5.4 | S |
| 1036 Ganymed | | 2.6597 | 0.5379 | 26.63 | 215.11 | 132.27 | 76.91 | 2449800.5 | 41 | S |
| 1221 Amor | 1932 EA1 | 1.9196 | 0.4353 | 11.89 | 170.83 | 26.30 | 229.59 | 2449800.5 | 1 | |
| 1580 Betulia | 1950 KA | 2.1946 | 0.4901 | 52.12 | 61.68 | 159.31 | 289.57 | 2449800.5 | 7.6 | C |
| 1627 Ivar | 1929 SH | 1.8632 | 0.3967 | 8.44 | 132.61 | 167.41 | 291.73 | 2449800.5 | 7.0 | S |
| 1915 Quetzalcoatl | 1953 EA | 2.5362 | 0.5741 | 20.46 | 162.36 | 347.90 | 177.59 | 2449800.5 | 0.5 | SMU |
| 1916 Boreas | 1953 RA | 2.2731 | 0.4494 | 12.83 | 340.20 | 335.27 | 54.42 | 2449800.5 | 3 | S |
| 1917 Cuyo | 1968 AA | 2.1513 | 0.5039 | 23.94 | 187.77 | 194.26 | 259.00 | 2449800.5 | 6 | |
| 1943 Anteros | 1973 EC | 1.4302 | 0.2559 | 8.70 | 245.73 | 338.20 | 287.25 | 2449800.5 | 2 | S |
| 1980 Tezcatlipoca | 1950 LA | 1.7096 | 0.3649 | 26.85 | 246.03 | 115.29 | 313.20 | 2449800.5 | 13 | SU |
| 2059 Baboquivari | 1963 UA | 2.6490 | 0.5264 | 11.00 | 200.43 | 191.17 | 102.17 | 2449800.5 | 2 | |
| 2061 Anza | 1960 UA | 2.2654 | 0.5365 | 3.76 | 207.07 | 156.42 | 40.91 | 2449800.5 | 3 | TCG |
| 2202 Pele | 1972 RA | 2.2900 | 0.5125 | 8.78 | 169.71 | 217.20 | 166.86 | 2449800.5 | 2 | |
| 2368 Beltrovata | 1977 RA | 2.1046 | 0.4138 | 5.24 | 287.05 | 42.24 | 273.73 | 2449800.5 | 3 | SQ |
| 2608 Seneca | 1978 DA | 2.4906 | 0.5816 | 15.34 | 168.91 | 33.90 | 118.21 | 2449800.5 | 1 | S |
| 3102 Krok | 1981 QA | 2.1523 | 0.4475 | 8.41 | 171.70 | 154.31 | 109.06 | 2449800.5 | 1 | QRS |
| 3122 Florence | 1981 ET3 | 1.7685 | 0.4227 | 22.17 | 335.53 | 27.55 | 155.48 | 2449800.5 | 6 | |
| 3199 Nefertiti | 1982 RA | 1.5743 | 0.2837 | 32.96 | 339.41 | 53.32 | 90.86 | 2449800.5 | 3 | S |
| 3271 | 1982 RB | 2.1024 | 0.3949 | 25.00 | 158.35 | 158.66 | 51.69 | 2449800.5 | 2 | |
| 3288 Seleucus | 1982 DV | 2.0325 | 0.4573 | 5.93 | 218.11 | 349.24 | 168.15 | 2449800.5 | 3 | S |
| 3352 McAuliffe | 1981 CW | 1.8784 | 0.3694 | 4.77 | 106.87 | 15.59 | 175.37 | 2449800.5 | 3 | |
| 3551 Verenia | 1983 RD | 2.0932 | 0.4866 | 9.50 | 173.29 | 193.06 | 287.25 | 2449800.5 | 1 | V |
| 3552 Don Quixote | 1983 SA | 4.2340 | 0.7141 | 30.78 | 350.02 | 316.59 | 121.87 | 2449800.5 | 18 | D |
| 3553 Mera | 1985 JA | 1.6446 | 0.3203 | 36.76 | 231.95 | 288.85 | 282.42 | 2449800.5 | 2 | |
| 3691 | 1982 FT | 1.7743 | 0.2839 | 20.37 | 348.24 | 234.61 | 161.62 | 2449800.5 | 5 | |
| 3908 | 1980 PA | 1.9241 | 0.4587 | 2.17 | 261.18 | 125.72 | 146.52 | 2449800.5 | 0.8 | V |
| 3988 | 1986 LA | 1.5446 | 0.3166 | 10.77 | 229.30 | 86.62 | 171.68 | 2449800.5 | 0.8 | |
| 4055 Magellan | 1985 DO2 | 1.8201 | 0.3263 | 23.24 | 164.29 | 154.11 | 253.29 | 2449800.5 | 3 | V |
| 4401 Aditi | 1985 TB | 2.5762 | 0.5676 | 26.79 | 23.31 | 67.08 | 83.58 | 2449800.5 | 3 | |
| 4487 Pocahontas | 1987 UA | 1.7302 | 0.2966 | 16.40 | 197.55 | 173.72 | 99.68 | 2449800.5 | 1 | |
| 4596 | 1981 QB | 2.2392 | 0.5188 | 37.12 | 153.80 | 248.30 | 354.00 | 2449800.5 | 2 | |
| 4688 | 1980 WF | 2.2347 | 0.5143 | 6.41 | 241.03 | 212.91 | 96.71 | 2449800.5 | 0.5 | QU |
| 4947 Ninkasi | 1988 TJ1 | 1.3696 | 0.1682 | 15.65 | 214.84 | 192.74 | 345.90 | 2449800.5 | 0.8 | |
| 4954 Eric | 1990 SQ | 2.0020 | 0.4481 | 17.47 | 358.12 | 52.01 | 188.99 | 2449800.5 | 12 | |
| 4957 Brucemurray | 1990 XJ | 1.5654 | 0.2189 | 35.01 | 254.29 | 97.46 | 115.89 | 2449800.5 | 4 | |
| 5324 Lyapunov | 1987 SL | 2.9591 | 0.6152 | 19.48 | 352.42 | 320.15 | 181.22 | 2449800.5 | 6 | |
| 5332 | 1990 DA | 2.1635 | 0.4564 | 25.43 | 142.48 | 305.56 | 235.47 | 2449800.5 | 7 | |
| 5370 Taranis | 1986 RA | 3.3469 | 0.6318 | 19.01 | 177.19 | 161.11 | 142.58 | 2449800.5 | 5 | |
| 5587 | 1990 SB | 2.3923 | 0.5483 | 18.09 | 189.88 | 86.19 | 110.92 | 2449800.5 | 7 | |
| 5620 | 1990 OA | 2.1591 | 0.4222 | 7.84 | 128.31 | 152.95 | 177.25 | 2449800.5 | 1.5 | |
| 5626 | 1991 FE | 2.1955 | 0.4543 | 3.86 | 172.87 | 231.07 | 168.09 | 2449800.5 | 4 | |
| 5646 | 1990 TR | 2.1420 | 0.4375 | 7.90 | 13.61 | 335.37 | 162.24 | 2449800.5 | 5 | |
| 5653 | 1992 WD5 | 1.7942 | 0.3038 | 6.86 | 9.50 | 122.15 | 315.07 | 2449800.5 | 3 | |
| 5751 | 1992 AC | 2.1045 | 0.4211 | 16.05 | 121.12 | 25.13 | 5.32 | 2449800.5 | 8 | |
| 5797 | 1980 AA | 1.8924 | 0.4441 | 4.18 | 298.41 | 168.13 | 303.93 | 2449800.5 | 0.6 | |
| 5836 | 1993 MF | 2.4438 | 0.5319 | 8.03 | 240.43 | 74.78 | 154.67 | 2449800.5 | 6 | |
| 5863 | 1983 RB | 2.2220 | 0.5062 | 19.43 | 168.79 | 114.78 | 192.76 | 2449800.5 | 3 | |
| 5869 Tanith | 1988 VN4 | 1.8121 | 0.3210 | 17.94 | 227.37 | 230.55 | 189.33 | 2449800.5 | 2 | |
| 5879 | 1992 CH1 | 1.6245 | 0.2893 | 21.57 | 145.27 | 355.45 | 183.08 | 2449800.5 | 1 | |
| 6050 | 1992 AE | 2.2027 | 0.4363 | 6.40 | 87.90 | 284.53 | 17.30 | 2449800.5 | 3 | |
| 6178 | 1986 DA | 2.8205 | 0.5823 | 4.29 | 64.41 | 126.87 | 321.62 | 2449800.5 | 4 | |
| | 1995 BK2 | 2.4417 | 0.5501 | 24.73 | 130.51 | 349.56 | 16.04 | 2449800.5 | 0.1 | |
| | 1995 BC2 | 1.9175 | 0.4304 | 5.02 | 328.01 | 81.19 | 55.76 | 2449800.5 | 2 | |
| | 1994 US | 2.7182 | 0.5671 | 8.46 | 223.06 | 121.45 | 44.21 | 2449800.5 | 0.2 | |
| | 1994 TE2 | 2.3043 | 0.4548 | 5.70 | 198.07 | 182.14 | 46.33 | 2449800.5 | 0.2 | |
| | 1994 TA2 | 2.6781 | 0.5312 | 7.07 | 200.47 | 119.12 | 52.54 | 2449800.5 | 0.3 | |
| | 1994 TW1 | 2.5912 | 0.5768 | 36.03 | 2.92 | 62.19 | 17.94 | 2449800.5 | 5 | |
| | 1994 RH | 2.2466 | 0.4414 | 18.92 | 330.99 | 91.81 | 23.17 | 2449800.5 | 3 | |
| | 1994 QC | 1.3243 | 0.1179 | 13.87 | 161.92 | 94.08 | 197.80 | 2449800.5 | 0.6 | |
| | 1994 PN | 2.3757 | 0.5400 | 46.05 | 112.54 | 233.88 | 40.75 | 2449800.5 | 2 | |
| | 1994 PC | 1.5683 | 0.3173 | 9.45 | 123.89 | 256.52 | 75.95 | 2449800.5 | 2 | |
| | 1994 NK | 2.3515 | 0.5387 | 5.67 | 119.54 | 128.48 | 82.34 | 2449800.5 | 0.4 | |
| | 1994 ND | 2.1663 | 0.5160 | 27.19 | 102.14 | 227.88 | 68.20 | 2449800.5 | 1 | |
| | 1994 LW | 3.1624 | 0.6195 | 23.02 | 240.44 | 54.41 | 41.52 | 2449800.5 | 2 | |
| | 1994 JX | 2.7372 | 0.5793 | 32.68 | 52.23 | 192.21 | 65.48 | 2449800.5 | 1 | |
| | 1994 GY | 2.6699 | 0.5318 | 12.46 | 33.43 | 189.95 | 72.14 | 2449800.5 | 2 | |
| | 1994 EF2 | 2.2919 | 0.5176 | 23.31 | 345.75 | 123.68 | 123.38 | 2449800.5 | 2 | |
| | 1994 BB | 2.0222 | 0.4257 | 1.14 | 122.19 | 335.84 | 154.30 | 2449800.5 | 0.1 | |
| | 1994 AW1 | 1.1046 | 0.0752 | 24.09 | 289.74 | 37.13 | 149.00 | 2449800.5 | 2 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1994 AB1 | 2.8432 | 0.5915 | 4.52 | 66.49 | 342.39 | 104.86 | 2449800.5 | 2 |
| 1993 VC | 2.7742 | 0.5330 | 3.20 | 241.94 | 177.04 | 102.41 | 2449800.5 | 0.3 |
| 1993 UD | 1.3194 | 0.1942 | 22.78 | 24.46 | 254.66 | 68.33 | 2449800.5 | 0.4 |
| 1993 UB | 2.2773 | 0.4602 | 25.02 | 30.83 | 20.78 | 138.90 | 2449800.5 | 2 |
| 1993 TQ2 | 1.9863 | 0.4198 | 6.04 | 13.01 | 77.24 | 158.63 | 2449800.5 | 0.4 |
| 1993 RA | 1.9276 | 0.4186 | 5.70 | 171.27 | 265.28 | 158.66 | 2449800.5 | 0.8 |
| 1993 QP | 2.3072 | 0.4693 | 7.24 | 296.70 | 46.55 | 159.58 | 2449800.5 | 1 |
| 1993 OM7 | 1.3398 | 0.2331 | 25.95 | 296.98 | 142.47 | 265.31 | 2449800.5 | 0.8 |
| 1993 MO | 1.6261 | 0.2208 | 22.63 | 110.90 | 167.06 | 296.20 | 2449800.5 | 2 |
| 1993 HO1 | 1.9872 | 0.4165 | 5.90 | 22.23 | 104.98 | 290.34 | 2449800.5 | 2 |
| 1993 HA | 1.2782 | 0.1442 | 7.73 | 182.76 | 263.47 | 234.13 | 2449800.5 | 0.4 |
| 1993 FS | 2.2267 | 0.4247 | 10.13 | 178.73 | 20.82 | 211.32 | 2449800.5 | 0.4 |
| 1993 DQ1 | 2.0399 | 0.4911 | 9.97 | 313.03 | 344.41 | 144.45 | 2449800.5 | 2 |
| 1993 BU3 | 2.4061 | 0.5142 | 5.29 | 315.61 | 144.39 | 215.05 | 2449800.5 | 0.2 |
| 1993 BD3 | 1.6346 | 0.3748 | 0.88 | 312.96 | 168.86 | 12.77 | 2449800.5 | 0.02 |
| 1993 BD2 | 2.1230 | 0.3933 | 25.59 | 96.50 | 65.06 | 221.55 | 2449800.5 | 0.6 |
| 1992 UB | 3.0658 | 0.5823 | 15.94 | 73.68 | 290.67 | 166.82 | 2449800.5 | 2 |
| 1992 TC | 1.5657 | 0.2923 | 7.08 | 88.11 | 275.36 | 95.98 | 2449800.5 | 1 |
| 1992 SZ | 2.1769 | 0.4599 | 9.27 | 3.74 | 314.60 | 292.98 | 2449800.5 | 0.4 |
| 1992 SL | 1.6415 | 0.3339 | 8.59 | 0.41 | 344.50 | 75.71 | 2449800.5 | 1. |
| 1992 OM | 2.1935 | 0.4087 | 8.21 | 313.15 | 346.80 | 298.57 | 2449800.5 | 2 |
| 1992 NA | 2.3910 | 0.5603 | 9.75 | 348.91 | 7.85 | 245.63 | 2449800.5 | 2 |
| 1992 LR | 1.8310 | 0.4090 | 2.02 | 232.38 | 67.85 | 26.56 | 2449800.5 | 1 |
| 1992 JE | 2.1895 | 0.4632 | 5.86 | 193.25 | 109.45 | 288.40 | 2449800.5 | 2 |
| 1992 BL2 | 1.6814 | 0.2300 | 36.86 | 297.15 | 23.40 | 311.09 | 2449800.5 | 4 |
| 1992 BA | 1.3412 | 0.0676 | 10.48 | 139.64 | 107.17 | 255.11 | 2449800.5 | 0.3 |
| 1992 AA | 1.9816 | 0.3897 | 8.29 | 102.15 | 354.30 | 54.79 | 2449800.5 | 2 |
| 1991 XB | 2.9552 | 0.5867 | 16.29 | 249.74 | 172.00 | 233.78 | 2449800.5 | 1 |
| 1991 RJ2 | 2.2105 | 0.4279 | 8.91 | 171.39 | 150.33 | 36.09 | 2449800.5 | 0.6 |
| 1991 PM5 | 1.7194 | 0.2551 | 14.42 | 132.09 | 140.27 | 244.15 | 2449800.5 | 1 |
| 1991 OA | 2.5081 | 0.5876 | 5.51 | 305.88 | 317.27 | 340.77 | 2449800.5 | 1 |
| 1991 NT3 | 1.8109 | 0.3041 | 13.86 | 286.78 | 292.75 | 226.14 | 2449800.5 | 5 |
| 1991 JG1 | 1.3732 | 0.1844 | 33.85 | 225.78 | 322.57 | 172.70 | 2449800.5 | 0.6 |
| 1991 JR | 1.4032 | 0.2598 | 10.11 | 59.50 | 207.11 | 96.35 | 2449800.5 | 0.1 |
| 1991 FB | 2.3675 | 0.5628 | 9.19 | 18.41 | 218.33 | 22.61 | 2449800.5 | 0.6 |
| 1991 FA | 1.9790 | 0.4467 | 3.07 | 338.84 | 91.76 | 210.37 | 2449800.5 | 2 |
| 1991 DB | 1.7163 | 0.4019 | 11.43 | 157.78 | 50.98 | 269.25 | 2449800.5 | 0.8 |
| 1990 VB | 2.4433 | 0.5277 | 14.56 | 253.91 | 102.25 | 60.05 | 2449800.5 | 2 |
| 1990 UP | 1.3253 | 0.1685 | 28.06 | 32.59 | 293.85 | 9.69 | 2449800.5 | 0.3 |
| 1990 SA | 1.9579 | 0.4295 | 37.53 | 171.69 | 114.31 | 260.05 | 2449800.5 | 2 |
| 1990 KA | 2.1987 | 0.4328 | 7.56 | 105.10 | 146.50 | 168.81 | 2449800.5 | 2 |
| 1990 BA | 1.7403 | 0.3376 | 1.99 | 311.17 | 170.79 | 88.00 | 2449800.5 | 1 |
| 1989 RS1 | 2.3039 | 0.4817 | 7.18 | 174.03 | 180.86 | 205.91 | 2449800.5 | 1 |
| 1989 RC | 2.3123 | 0.5138 | 7.38 | 139.68 | 181.09 | 213.16 | 2449800.5 | 1 |
| 1989 OB | 2.6963 | 0.5594 | 7.91 | 289.02 | 71.72 | 84.97 | 2449800.5 | 2 |
| 1989 ML | 1.2723 | 0.1364 | 4.37 | 103.83 | 183.10 | 350.60 | 2449800.5 | 0.5 |
| 1988 SM | 1.6628 | 0.3433 | 10.92 | 0.38 | 312.92 | 30.25 | 2449800.5 | 1 |
| 1988 PA | 2.1502 | 0.4077 | 8.21 | 161.74 | 136.95 | 41.55 | 2449800.5 | 2 |
| 1988 NE | 2.1808 | 0.4424 | 9.93 | 253.53 | 354.81 | 42.48 | 2449800.5 | 0.8 |
| 1987 WC | 1.3619 | 0.2336 | 15.83 | 51.27 | 308.10 | 261.24 | 2449800.5 | 0.5 |
| 1987 SF3 | 2.2541 | 0.5333 | 3.32 | 187.02 | 133.63 | 88.85 | 2449800.5 | 0.8 |
| 1987 QB | 2.7927 | 0.5975 | 3.48 | 152.88 | 156.10 | 228.26 | 2449800.5 | 0.6 |
| 1987 PA | 2.7172 | 0.5640 | 16.35 | 307.97 | 337.77 | 258.27 | 2449800.5 | 0.8 |
| 1986 NA | 2.1260 | 0.4495 | 10.34 | 243.21 | 35.68 | 293.62 | 2449800.5 | 0.4 |
| 1985 WA | 2.8345 | 0.6058 | 9.78 | 43.00 | 351.11 | 344.97 | 2449800.5 | 0.8 |
| 1983 LB | 2.2865 | 0.4770 | 25.35 | 80.82 | 220.18 | 132.56 | 2449800.5 | 2 |
| 1982 YA | 3.6952 | 0.6993 | 34.90 | 268.91 | 143.80 | 264.76 | 2449800.5 | 4 |
| 1977 VA | 1.8642 | 0.3940 | 2.98 | 223.94 | 172.37 | 299.74 | 2449800.5 | 0.6 |
| 1977 QQ5 | 2.2256 | 0.4662 | 25.20 | 133.83 | 247.77 | 88.64 | 2449800.5 | 4 |
| 1972 RB | 2.1499 | 0.4856 | 5.22 | 176.81 | 152.34 | 59.99 | 2449800.5 | 0.6 |
| 4788 P-L | 2.6274 | 0.5501 | 10.98 | 176.92 | 97.14 | 69.97 | 2449800.5 | 2 |

---

Go to: Near Earth Asteroids

# Appendix III

```
// Melissa Wright
// Masters in Space Operations
// Creative Investigation program
// 3 April, 1998



#include <stdio.h>
#include <math.h>
#include <iostream.h>
#include <fstream.h>

double TAnomaly(double, double);
double ETAnomaly(double, double);
double PKepler(double, double, double, double, double, double);


main()
{
    double Pi, e, M, node, peri, a, Ee, EM, Enode, Eperi, Ea;
    double Ev, v, n, En, EAngle, Angle, Total, Mnew, EMnew, R;
    int JD, x;

    Pi = 3.14159265359;

    ofstream out ("1987OA.txt");  // Name of file is name of asteroid

    e = 0.5956;       // Orbital elements for the asteroid in question
    M = 22.98;        // Degrees
    node = 179.69;    // Degrees
    peri = 235.38;    // Degrees
    a = 1.4962;       // AU s

    M = (M*Pi)/180;
    node = (node*Pi)/180;
    peri = (peri*Pi)/180;
    a = a*149597870.0;
    n = sqrt(132712428000/(pow(a,3)));

    Ee = 0.0167;                // All of these for JD = 2451545 (JD2000)
    EM = 357.5291;              // Equals lamdaM - omegasqiggle = -2.4709 degrees
    Enode = 0.0000;             // All in degrees
    Eperi = 102.9373 - Enode;   // Equals  omegasquiggle - node
    Ea = 149597870.0;           // In km already

    EM = (EM*Pi)/180;           // JD = 2451545
    Enode = (Enode*Pi)/180;
    Eperi = (Eperi*Pi)/180;

    En = sqrt(132712428000/(pow(Ea,3)));

    Mnew = M + (n*95472000);    //Propagating M from 2449800 to 2450905
    EMnew = EM - (En*55296000); // And EM backwards to 2450905 (12 00, April 1, 1998)

    while (Mnew > (2*Pi))
        Mnew = Mnew - (2*Pi);
    while (EMnew < (0))
        EMnew = EMnew + (2*Pi);

    x = 0;
```

```
    JD = 2450905;


    while (x < 184)             //Want 183 iterations (10 day intervals for 5 years)
    {
    Ev = ETAnomaly (Ee, EMnew);
    v = TAnomaly (e, Mnew);

    Angle = node + peri + v;
    EAngle = Enode + Eperi + Ev;

    while (Angle < 0)
        Angle = Angle + (2*Pi);
    while (Angle > (2*Pi))
        Angle = Angle - (2*Pi);
    while (EAngle < 0)
        EAngle = EAngle + (2*Pi);
    while (EAngle > (2*Pi))
        EAngle = EAngle - (2*Pi);

    Total = EAngle - Angle;
    if (Total < 0)
        Total = -Total;
    if (Total > Pi)              // To get the smallest difference in true anomalies
        Total = 2*Pi - Total;
    Total = (Total*180)/Pi;      // Put in degrees


    if(Total < 15)               // Measure difference in r's IF angle between asteroid
    {                            // and Earth is < 30 degrees

      R = PKepler(Ea, Ee, Ev, a, e, v);   // R is returned in AUs
     if(R < 1.0)                          // Only want R s less than 1 AU
     {out << "\n R is  " << R;
      out << "   Angle difference = " << Total;
      out << "  JD = " << JD;
     }

    }

    Mnew = Mnew + (n*864000);    //Propagating M's by 10 days
    EMnew = EMnew + (En*864000);
    while (Mnew > (2*Pi))
        Mnew = Mnew - (2*Pi);
    while (EMnew > (2*Pi))
        EMnew = EMnew - (2*Pi);

    JD = JD +10;
    x = x+1;
    }

    out.close();
}



// Function finds Earth true anomaly at a given JD :
```

```
double ETAnomaly (double Ee, double EMnew)
{
   double Pi, E0, E1, Ev,term, sinv1, cosv1;
   int x;

   Pi = 3.14159265359;

   E0 = EMnew;
   x = 0;

    while( x < 1000)                                // Propagating for E
    {
     E1 = E0 + ( (EMnew - E0 + (Ee*sin(E0)) ) / (1 - Ee*cos(E0)) );
     if( E1 > E0)
     {   if (E1 - E0 < 0.00001)
             x = 1001;
     }
     else
     { if (E0 - E1 < 0.00001)
           x = 1001;
     }

     E0 = E1;
     x = x + 1;

    }

   term = sqrt(1 - pow(Ee,2));

   sinv1 = (term*sin(E1)) / (1 - Ee*cos(E1));
   cosv1 = (cos(E1) - Ee) / (1 - Ee*cos(E1));
   Ev = atan2(sinv1,cosv1);                    // Finding true anomaly & checking quadrants

   return Ev;
}




// Function finds asteroid true anomaly at a given JD :

double TAnomaly(double e, double Mnew)
{
   double E0, E1, v, Pi, term, sinv1, cosv1;
   int x;

   Pi = 3.14159265359;

   E0 = Mnew;
   x = 0;

    while( x < 1000)                                // Propagating for E
    {
     E1 = E0 + ( (Mnew - E0 + (e*sin(E0)) ) / (1 - e*cos(E0)) );
     if( E1 > E0)
     {   if (E1 - E0 < 0.00001)
             x = 1001;
     }
```

```
    else
      { if (E0 - E1 < 0.00001)
            x = 1001;
      }

      E0 = E1;
      x = x + 1;

     }

   term = sqrt(1 - pow(e,2));

   sinv1 = (term*sin(E1)) / (1 - e*cos(E1));
   cosv1 = (cos(E1) - e) / (1 - e*cos(E1));
   v = atan2(sinv1,cosv1);                    // Finding true anomaly & checking quadrants
   return v;
}




// Function finds the difference in  Earth and Asteroid r vectors (in the PQW frame)

double PKepler(double Ea, double Ee, double Ev, double a, double e, double v)
{ double p1, p2, Er1, Er2, Er3, r1, r2, r3;
  double R1, R2, R3, R;

  Ea = Ea / 149597870;                        // Change to AUs
  p1 = Ea*(1 - pow(Ee, 2));
  Er1 = (p1*cos(Ev)) / (1 + Ee*cos(Ev));      // The Earth's r vector
  Er2 = (p1*sin(Ev)) / (1 + Ee*cos(Ev));
  Er3 = 0;

  a = a / 149597870;                          // Change to AUs
  p2 = a*(1 - pow(e, 2));
  r1 = (p2*cos(v)) / (1 + e*cos(v));          // The asteroid's r vector
  r2 = (p2*sin(v)) / (1 + e*cos(v));
  r3 = 0;

  R1 = r1 - Er1;                              // Figure the difference in r's
  R2 = r2 - Er2;
  R3 = r3 - Er3;

  R = sqrt(pow(R1,2) + pow(R2,2) + pow(R3,2));    // Find the magnitude of R
  return R;
}
```

# Appendix IV

```
R is  0.619971   Angle difference = 10.7427  JD = 2452165
R is  0.536488   Angle difference = 5.63706  JD = 2452175
R is  0.472445   Angle difference = 0.937095  JD = 2452185
R is  0.427186   Angle difference = 3.27842  JD = 2452195
R is  0.39748   Angle difference = 6.91406  JD = 2452205
R is  0.377872   Angle difference = 9.85718  JD = 2452215
R is  0.362097   Angle difference = 11.9804  JD = 2452225
R is  0.344581   Angle difference = 13.1506  JD = 2452235
R is  0.321292   Angle difference = 13.2485  JD = 2452245
R is  0.290002   Angle difference = 12.2052  JD = 2452255
R is  0.25027   Angle difference = 10.0547  JD = 2452265
R is  0.203286   Angle difference = 6.98881  JD = 2452275
R is  0.151515   Angle difference = 3.37894  JD = 2452285
R is  0.0980593   Angle difference = 0.275011  JD = 2452295
R is  0.0463143   Angle difference = 3.46354  JD = 2452305
R is  0.0193329   Angle difference = 5.79214  JD = 2452315
R is  0.0627334   Angle difference = 7.04303  JD = 2452325
R is  0.114805   Angle difference = 7.16175  JD = 2452335
R is  0.1726   Angle difference = 6.20442  JD = 2452345
R is  0.238753   Angle difference = 4.28346  JD = 2452355
R is  0.315456   Angle difference = 1.52905  JD = 2452365
R is  0.403969   Angle difference = 1.9326  JD = 2452375
R is  0.504691   Angle difference = 5.98921  JD = 2452385
R is  0.61737   Angle difference = 10.5455  JD = 2452395
```