NASA'S NEAR-EARTH OBJECT OFFICE

Donald K. Yeomans, Paul W. Chodas, Alan B. Chamberlin

Jet Propulsion Laboratory/Caltech, Pasadena, CA 91109

ABSTRACT

Near-Earth Objects (NEOs) are scientifically interesting remnants of the early solar system formation process, accessible resources for the raw materials necessary for colonizing the inner solar system in the next century, and objects that can threaten life on Earth. The number of these objects larger than 1 km in size is estimated to range from 750 to 1500, but only about 300 of them have been discovered to date. In order to evaluate the threat posed by these objects, we must discover the majority of the remaining population. At least seven major discovery programs are underway or are in the planning stages. NASA has made it a goal to realize the aim of the Spaceguard Survey, which is to discover at least 90 percent of all NEOs with diameters greater than 1 km within 10 years. Physical characterization of NEOs using ground-based photometric, spectral, and radar observations, along with in situ measurements from spacecraft, all contribute to a better understanding of these objects. NASA's Near-Earth Object Office at JPL has begun the effort of communicating the importance of NEO research to the public. An award-winning web page (http://neo.jpl.nasa.gov) has been established to communicate with the public and the NEO scientific community. Within the Near-Earth Object Office, a semi-automatic process is in place to provide daily orbital updates for those comets and asteroids that can closely approach the Earth. In addition, future Earth close approaches and associated impact probabilities are computed daily. While no known NEO has any significant chance of impacting the Earth in the next fifty to a hundred years, the future motion of each newly discovered NEO is investigated in near real time to determine if it is benign or a potential threat to Earth.

INTRODUCTION

For a few days in March 1998, the world press reported that a kilometer-sized asteroid named 1997 XF_{11} might strike the Earth in October 2028. The asteroid had been discovered on December 6, 1997 by Jim Scotti using the Spacewatch Telescope on Kitt Peak, and had been placed on the Minor Planet Center's list of Potentially Hazardous Asteroids soon afterwards. After a month, its orbit was well enough determined for the Center to predict that the asteroid would pass quite close to Earth on October 26, 2028 - within a million kilometers. The asteroid was well observed for another month, but then went unobserved for four weeks. When Peter Shelus at the McDonald Observatory in Texas picked it up again on the nights of March 3 and 4, his four observations extended the data arc significantly, to 88 days, and changed the orbit solution significantly as well. The new miss distance in 2028 had shrunk to less than a quarter of a lunar distance, and possibly even smaller, making it easily the closest-ever predicted close approach of an asteroid to the Earth. Figure 1 shows that Earth close approaches with asteroid 1997 XF_{11} are possible since the asteroid crosses southward through the Earth's orbital plane very close to the Earth's orbital distance. On March 11, 1998 the Minor Planet Center announced the predicted extreme close approach of this asteroid in an IAU Circular[1], adding that passage within one lunar distance was "virtually certain". An accompanying press statement noted that "The chance of an actual collision is small, but one is not entirely out of the question."

However, the authors of this paper undertook a complete analysis of the observations available on March 11 and showed that the probability of impact in 2028 was negligible, essentially zero. Orbital uncertainties and impact probabilities are often visualized using so-called uncertainty ellipses – ellipsoidal regions of space surrounding a nominal asteroid position where the object could be located. Figure 2 shows the 3-sigma position uncertainty ellipse in the target plane at closest approach (sigma denotes standard deviation). The ellipse is extremely elongated, about 2.8 million kilometers long, but only 2,500 km wide. The extreme length of the ellipse is due to the fact that the position uncertainty along the orbit grows linearly with time over the 30-year prediction period, while uncertainty perpendicular to the orbit varies only periodically. The 30-year projection into the future spans 17 revolutions of the asteroid about the Sun. Since the ellipse extends well beyond the Moon's orbit, passage outside one lunar distance is very possible. The great length of the ellipse in Figure 2 makes it difficult to predict a precise miss distance, since passage virtually anywhere within the ellipse is possible. The narrow width of the ellipse, however, allows a fairly precise determination of the minimum possible miss distance, about 28,000 km. One can use the analogy of a car waiting at an intersection for a train to pass by on its long track. The car's driver cannot predict the exact arrival time of the train at his intersection (large along track uncertainty) but he can be confident that the train will not deviate from the track itself. That is, the uncertainty of the train's position, at any given time, is almost completely in one direction. Figure 3 shows a close up of the region of the target plane near the Earth. The ellipse would have to be enlarged to about the 55-sigma level before it would graze the Earth.

On March 12, Ken Lawrence and Eleanor Helin, both of JPL, found four pre-discovery images of the asteroid, taken in 1990. These extended the data arc greatly to 8 years, strengthening the orbital solution. The predicted close approach in 2028 moved out to a rather unremarkable 980,000 km, while the uncertainty ellipse shrank by over an order of magnitude. Figure 4 shows the uncertainty ellipse for the orbit solution including the 1990 observations. While the new observations moved the predicted miss distance to a comfortable range, they were not needed to rule out the possibility of collision in 2028.

While the concern associated with the Earth close approach of asteroid 1997 XF_{11} was not responsible for the establishment of NASA's Near-Earth Object Office, this incident did highlight some problems concerning NEOs that needed to be addressed. A reliable process had to be put in place to ensure that the orbits and future motions of all asteroids and comets that can approach the Earth are carefully monitored and accurate Earth impact probabilities are computed. In addition, an effort had to be undertaken to optimize, to the extent possible, the independent NEO search teams that are currently operational. An up-to-date, easily accessible near-Earth object web site needed to be established to maintain contact with the public, to keep them informed about NEO activities, coming close Earth approaches, missions to comets and asteroids and the reasons for the intense interest in these, the Earth's closest neighbors. This paper will discuss, in turn, the population of NEOs and the establishment and activities of NASA's Near-Earth Object Office. After a brief discussion of the current operational search teams, a recent example will be provided to show how the proper procedures and analyses were undertaken to defuse concern over an asteroid (1999 AN_{10}) that was thought, for a time, to have a non-zero chance of hitting the Earth within the next few decades.

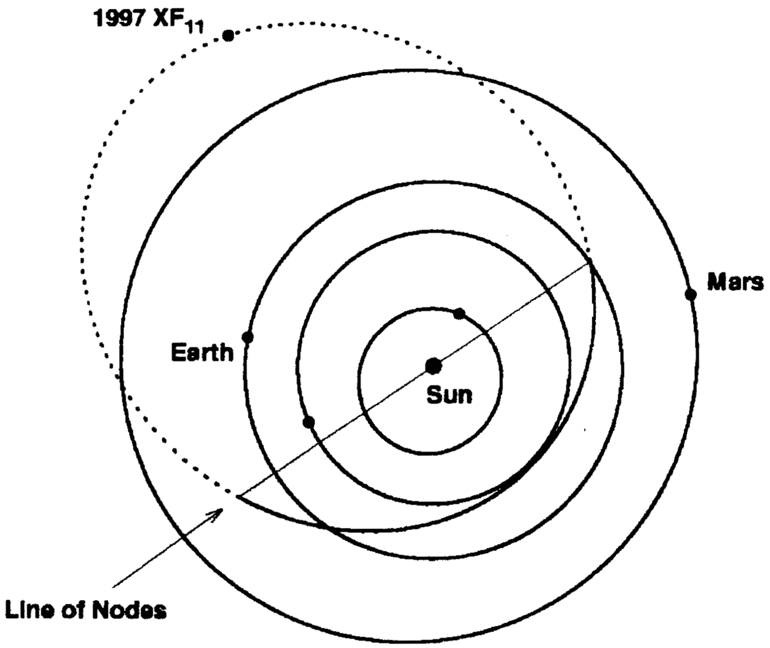

Figure 1 Orbit of Asteroid 1997 XF_{11}
(Orbit inclined 4.1° to ecliptic plane; dotted portion is below ecliptic)

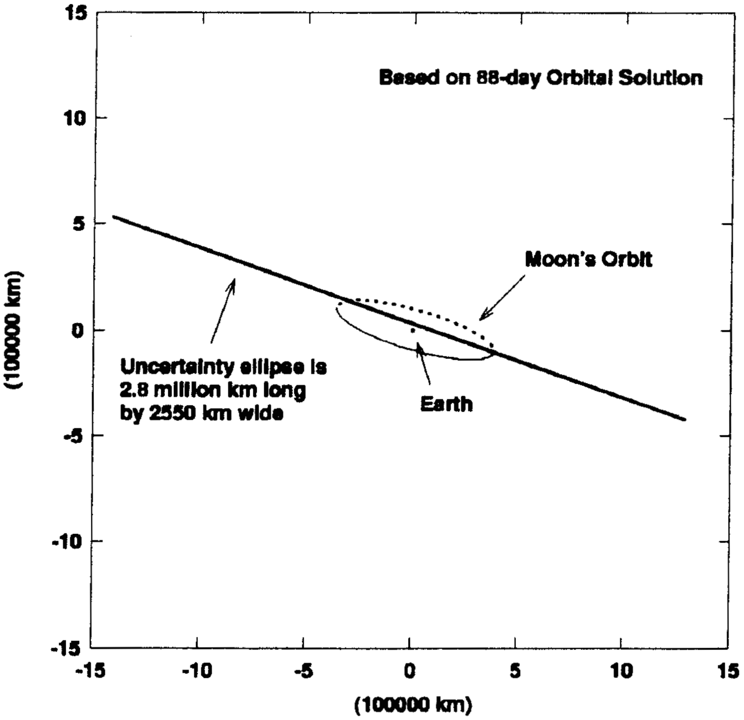

Figure 2 Position Uncertainty Ellipse for 1997 XF_{11} in Target Plane on Oct. 26, 2028, 88-day Orbital Solution

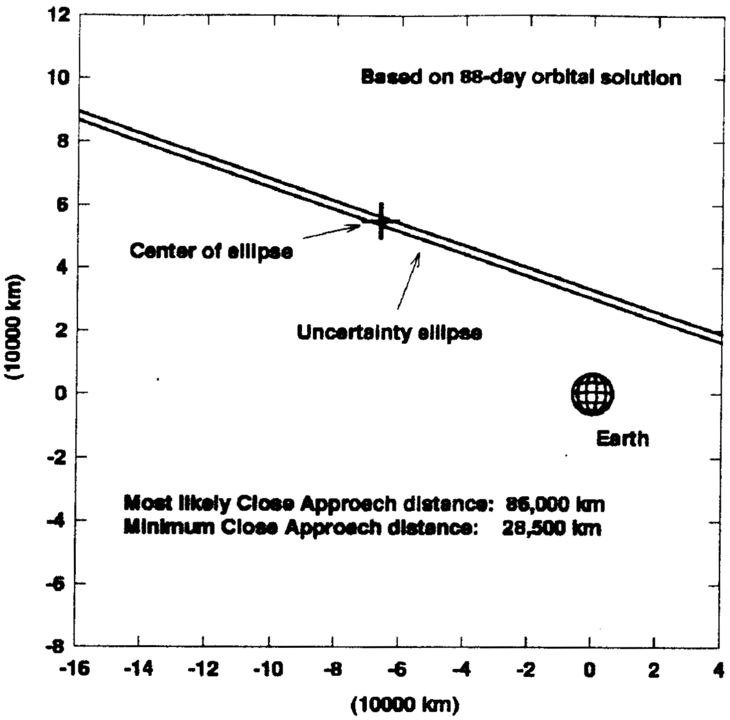

Figure 3 Enlargement of Central Part of Figure 2

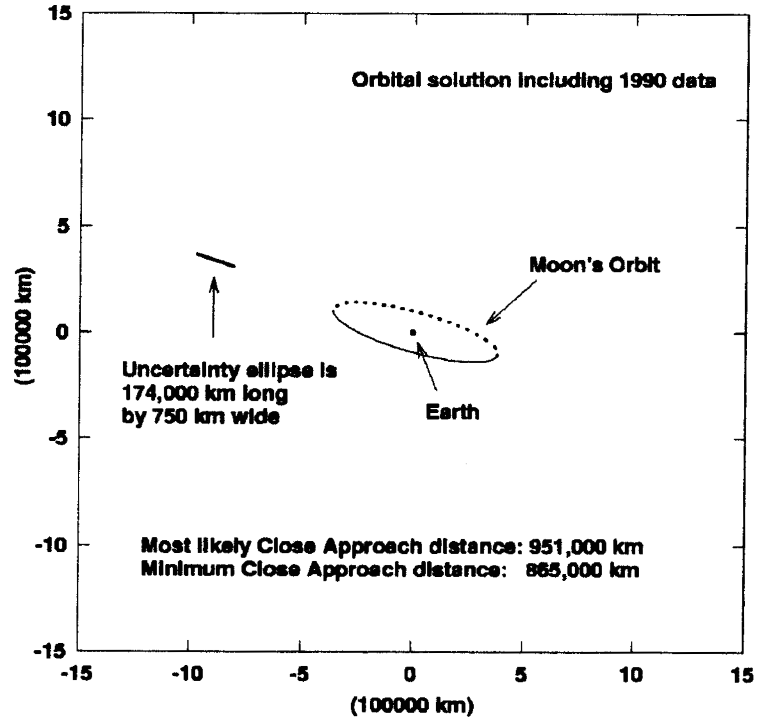

Figure 4 Position Uncertainty Ellipse for 1997 XF$_{11}$ in Target Plane on Oct. 26, 2028, Orbital Solution Including 1990 Observations

NASA'S NEAR-EARTH OBJECT OFFICE

The Near-Earth Object Office was established by NASA Headquarters in late 1998 to act as a focus for NASA's contributions in discovering and monitoring the motions of the NEO population. In particular, the charter of the NEO Office includes efforts to:

1. Facilitate communication both within the observing community and between the community and the public with respect to any potentially hazardous objects (PHOs) which are discovered and provide a focus for public inquiries about these objects.
2. Establish, update and maintain a catalog of NEOs together with an estimate of the quality of the orbital elements accessible to the scientific community and the public.
3. Develop and support a strategy and plan for the scientific exploration of NEOs including their discovery, recovery, ephemerides, characterization, in-situ investigations, and resource potential. Support NASA Headquarters in coordinating with other government agencies and with foreign governments and international organizations on NEO issues.
4. Coordinate ground-based observations in order to complete the survey of NEOs, and to obtain accurate orbital elements for newly discovered NEOs based upon the best available data.

The principal vehicle for the communication of information on NEOs to the scientific community and to the public is via our interactive web page: http://neo.jpl.nasa.gov. This award winning site includes written summaries of the NEO discovery teams and the current space missions to comets and asteroids, comet and asteroid images and recent news items relating to NEOs. The user can request, and download, tailor-made tables of orbital data and ephemeris information for all comets and asteroids with well defined orbits (more than 20,000 objects). This web site also allows the user to display tables of Earth close approaches for the past and future. Tables of future close approaches are updated daily as new data become available for the potentially hazardous asteroids (PHAs). Currently the closest nominal Earth approach will take place on 2027 August 7 when asteroid 1999 AN_{10} passes within one lunar distance of the Earth. The next two nominal closest Earth approaches (both to within 2.2 lunar distances) are asteroids 1999 MN on June 3, 2010 and 2340 Hathor on October 21, 2086.

Within the NEO Office website activities, we have implemented a semi-automated process to maintain an up-to-date database of PHA orbit solutions and close-approach predictions. This process runs on a daily basis because it is essential to use the latest set of observations for each object, particularly when these new data extend the available data interval. Minor Planet Center electronic circulars are checked daily for new PHAs and for the associated astrometric data. If a new PHA is detected, all available optical and radar data are used to update the object's orbit and the object's motion is numerically integrated forward for 100 years. Close approaches to all perturbing bodies are then identified. Uncertainties at each close approach are estimated by linearly mapping orbital uncertainties to the close approach and projecting these into the impact plane (the plane perpendicular to the incoming asymptote). The dimensions of the impact-plane uncertainty ellipse and its position relative to the target body are calculated as well as the uncertainty in the close approach time. An estimate of the impact probability is also computed[4]. For those PHAs that make particularly close approaches to the Earth, or repeated Earth close approaches, fully non-linear methods including Monte Carlo simulations, are used to make the necessary computations[5].

The scientific exploration of NEOs requires the ground-based efforts to first discover most of the large NEOs followed by the physical characterization of a suitable fraction of these objects. Finally the detailed characterizations of a few representative bodies via in situ spacecraft observations is necessary. While ground-based optical and radar observations can help

THE POPULATION OF NEAR-EARTH OBJECTS

Near-Earth Objects (NEOs) are asteroids and comets that have been nudged by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth's neighborhood. Most of the rocky asteroids we see today formed in the inner Solar System from debris leftover from the initial agglomeration of the inner planets, Mercury through Mars. Comets, on the other hand, are composed mostly of water ice with embedded dust particles, and originally formed in the cold outer planetary system, leftover bits from the formation of the giant outer planets, Jupiter through Neptune. Scientific interest in these objects is due largely to their status as the relatively unchanged remnant debris, the primitive, leftover building blocks of the solar system formation process. They offer clues to the chemical mixture of the primordial material from which the planets were formed some 4.6 billion years ago. But these small bodies are interesting also because of the hazard they pose to the Earth. Even though the accretion phase of the Solar System ended long ago, as did the "heavy bombardment" phase, which produced most of the scars we see today on our Moon, Mercury, and other primitive bodies, the process of accretion and bombardment has not completely abated. Today, the Earth is still accumulating interplanetary material at the rate of about one hundred tons per day, although most of it is in the form of tiny dust particles released by comets as their ices vaporize in the solar neighborhood.

The vast majority of the larger interplanetary material that reaches the Earth's surface originates as fragments from the collision of asteroids eons ago. Larger pieces of debris hit the Earth less frequently simply because there are fewer of them. Van-sized asteroids impact the Earth approximately every few years, but typically disintegrate into small pieces before hitting the ground. Asteroids larger than about 50 meters, however, may well reach our surface largely in one piece, depending on their composition, and these impacts are estimated to occur approximately every few hundred years. An impact of this size would certainly cause a local disaster, and if it occurred in the ocean, it might produce a strong tidal wave that could inundate low lying coastal areas. On average, every few hundred thousand years or so, an asteroid larger than a kilometer will impact the Earth, and an impact of this size would almost certainly cause a global catastrophe. In this case, the impact debris would spread throughout the Earth's atmosphere so that plant life would suffer from acid rain, partial blocking of sunlight, and from the firestorms resulting from heated impact debris raining back down upon the Earth's surface. Even though asteroid and comet impacts of this sort are extremely infrequent, the enormous consequences of these events make it prudent to mount efforts to discover and study these objects, to characterize their sizes, compositions and structures and to keep an eye upon their future trajectories.

Although the term near-Earth objects (NEOs) is often used to describe those comets and asteroids that can closely approach the Earth over millions of years, it is only the sub-class of so-called potentially hazardous objects (PHOs) that have the ability to approach the Earth over time spans of decades or centuries. PHOs are somewhat arbitrarily defined as those objects whose absolute magnitude is 22 or brighter (diameters larger than about 150 m) that can approach the Earth's orbit to within 0.05 AU (about 7.5 million km).

While there had been concern within the scientific community over collisions of asteroids and comets with the Earth for some time[2], the dramatic collision of comet Shoemaker-Levy 9 with Jupiter in July 1994 was particularly effective in engaging the public. These widely reported collisions continued over seven days (July 16 – 22) and as fragment after fragment collided with Jupiter, these events went a long way in convincing skeptics that the threat of NEOs to Earth was real and should be dealt with seriously. These events also prompted efforts at JPL to develop the sophisticated software necessary to correctly compute the times and locations of the impacts and the time dependence of the impact probabilities as more and more astrometric data were processed[3].

processing by a computer. A fairly common astronomical CCD detector might have dimensions of 2096 × 2096 pixels. The basic detection method is very similar to that used with the older photographic methods, but the detection is now automated using sophisticated computer-aided analyses of the CCD images. Separated by several minutes, three or more CCD images are taken of the same region of the sky. The algorithm then compares these images to see if any objects have systematically moved from one frame to the next. Once a moving object has been detected, the separation of the images in the successive frames, the direction of travel, and the object's brightness all are helpful in identifying how close the object is to the Earth, and its approximate size and orbital characteristics. In particular, an object that appears to be moving very rapidly from one frame to the next is almost certainly very close to the Earth.

At least seven major NEO search programs are either in operation or in the planning stages. The oldest of these is the Spacewatch program, which has been operational since 1984 on Kitt Peak, near Tucson, Arizona. A second program, called the Near-Earth Asteroid Tracking (NEAT) program, is run by the Jet Propulsion Laboratory using Air Force telescope facilities on Maui. Another search team that uses Air Force telescopes is the Lincoln Near-Earth Asteroid Research program (LINEAR) , a joint effort between the Air Force and the MIT Lincoln Laboratory, operating at Socorro, New Mexico. Using state-of-the-art detector technology, the LINEAR program is making the majority of the current discoveries. The Lowell Observatory Near-Earth Object Search program (LONEOS) operating near Flagstaff, Arizona has recently come on line. A European cooperative NEO discovery effort between the Observatoire de la Côte d'Azur (OCA) in southern France and the Institute of Planetary Exploration (DLR) in Berlin, Germany, was initiated in October 1996. Another successful discovery effort near Tucson called the Catalina Sky Survey has recently become operational and in 2001, a Japanese search effort run by the Japan Spaceguard Association will begin operation.

In 1998, NASA made it a goal to help realize the aim of the Spaceguard Survey, namely to discover at least 90% of all NEOs whose diameters are larger than 1 kilometer within 10 years. While it is doubtful that the current discovery rate is in line with reaching the Spaceguard goal, there has been a significant increase over the rate only a few years earlier. With the promise of additional programs coming online and the bugs being worked out of some of the newer programs, we may soon approach the discovery rate needed to achieve the Spaceguard goal.

THE CASE OF ASTEROID 1999 AN_{10}

In April 1999, another potentially hazardous asteroid, 1999 AN_{10}, made the news because of a remote possibility that it might collide with Earth. The story of this asteroid is remarkably similar to that of 1997 XF_{11}, except that, fortunately, no incorrect claims were made that an impact was possible during the asteroid's first deep approach to the Earth. The asteroid was discovered on January 13, 1999 by the Lincoln Near-Earth Asteroid Research (LINEAR) program operated by MIT's Lincoln Laboratory in cooperation with the U.S. Air Force. Based on its brightness, the object was estimated to be just over one kilometer in size, close to the most dangerous size range. The asteroid's orbit is somewhat unusual because it passes fairly close to the Earth's orbit not just once, but twice on each 643-day circuit about the Sun, both inbound towards the Sun and outbound from the Sun.

Unfortunately, 1999 AN_{10} was observed for less than 6 weeks before it moved into the glare of the Sun, and because this data arc was so short, predictions of the asteroid's motion were very uncertain. A deep close approach to the Earth was possible on August 7, 2027, but the uncertainty region for this close approach was much larger even than that for the 2028 encounter of 1997 XF_{11} before its pre-discovery observations were found. The minimum possible close determine an object's orbit, rotation state, spectral class, albedo and size, the detailed analysis of an object's elemental composition (and hence its link to an appropriate meteorite type) will require in situ spacecraft investigations. The necessary measurements must be made during a rendezvous mission using instruments such as X-ray and gamma ray spectrometers. Over the next thirteen years, seven spacecraft (NEAR, Stardust, DS1, MUSES-C, CONTOUR, Deep Impact, Rosetta) are scheduled to flyby or rendezvous with twelve different comets and asteroids. Under the auspices of the Interagency Consultative Group (IACG), the NEO Office is facilitating efforts for cooperation among these flight projects. While none of these projects has the resources to support new initiatives, discussions are proceeding in an effort to identify areas where one project may be able to share information or data with another. For example, a good deal of work has already been done in modeling the surfaces of comets and asteroids and these models could be made available to all the flight projects. In addition, ground-based observers can easily provide astrometric and physical characterization data on more than one mission target during a particular observing period. These data could also be shared among the various flight projects.

Because each of the NEO discovery teams operates as an independent entity funded as a result of the peer review process, comprehensive efforts to coordinate their efforts would be difficult, and partially counter-productive. It could be argued that some competition between the various teams is beneficial. Even so, some cooperative efforts would make the entire search effort more efficient and there have been significant efforts between the teams to "share the sky" so that Team B is not always looking where Team A was looking the previous evening. For example, the LINEAR discovery team currently covers the largest area of the sky each month and they post on the web the fields where they searched the previous evening. In addition to the discovery observations, follow-up observations are necessary to ensure newly discovered objects are not lost. In this regard, the Lowell Observatory's LONEOS project provides a web-based service whereby observers can determine the optimal time to make follow-up observations to ensure that an object's orbit will be secure. The following section briefly describes the major, active NEO discovery teams.

NEO SEARCH PROGRAMS

In 1990, the U.S. Congress directed NASA to organize a workshop to study ways of significantly increasing the rate of discovery of near-Earth asteroids (NEAs). The resulting workshop produced a proposal for an international program called the Spaceguard Survey, with the goal of discovering 90% or more of the NEAs larger than 1 km across within 10 years[6]. This size range was chosen because it poses the greatest impact hazard for our civilization on Earth. The estimated number of NEAs in this class is currently thought to be in the range of 750 to 1500, but only 304 of this number had been discovered by mid-July 1999. Although the network of six 2.5-meter telescopes proposed to implement the Spaceguard Survey was never funded, the accelerating pace of technology has enabled smaller and less expensive telescopes with modern detectors to achieve, at least partially, the discovery rate needed to complete the Spaceguard Survey.

Early efforts to discover NEOs relied upon photographic methods. Two plates or films of a given region of the sky would be taken many minutes apart, and then viewed through an instrument such as a special stereo viewing microscope. Any moving object such as an NEO would appear in a slightly different position on the two photographs, and, when viewed in stereo, the object would appear to "rise" above the background stars and galaxies, making it easy to find, but still a very labor-intensive operation.

Currently, NEO discovery teams use so-called charged couple devices (CCDs). These electronic detectors are not only more sensitive and accurate than the older photographic method, but they also record images digitally in arrays of picture elements (pixels), a form amenable to automated approach distance for 1999 AN_{10} was a little larger, about 38,000 km from the center of the Earth -- an impact was therefore not possible in 2027. But what about impacts after 2027?

Andrea Milani and his colleagues in Italy had been independently developing non-linear techniques for analyzing close approaches, with the idea of applying these to the case of 1997 XF_{11}. When these methods were applied to the case of 1999 AN_{10}, it was found that one of the predicted close Earth approaches could result in an impact, with a probability on the order of one in a billion. In late March, Milani et al. circulated a preprint which announced this remote possibility of impact for 1999 AN_{10}, and outlined a theory which predicted both its resonant and non-resonant returns[7,8]. (Non-resonant returns referred to trajectories which took the asteroid from an encounter at one node to an encounter at the other node.)

The impacting scenario identified by Milani et al. was for the year 2039, but it actually required that 1999 AN_{10} pass through two very narrow regions in space ("keyholes"), one in the 2027 confidence region, which would take it to a 2034 close approach, and then through a second keyhole in the 2034 confidence region. This partly explained why this scenario was so unlikely. At one-in-a-billion, this impact probability was so extremely miniscule, that it was tens of thousands of times smaller than the probability of an undiscovered asteroid of equivalent size hitting the Earth during the same 40-year period. However, the asteroid certainly deserved to be watched carefully, as Milani et al. had found that its orbit would remain threateningly close to the Earth's orbit for many centuries to come. Fortunately, in just a few months, the asteroid would become observable again, as it moved back into the twilight sky. It was expected that the new observations would, in all likelihood, completely eliminate the possibility of impact in 2039.

New observations for 1999 AN_{10} were indeed made in mid-May, 1999, by amateur astronomer Frank Zoltowski in Australia. As expected, these enabled much more precise orbital calculations, and the revised predictions indicated that the asteroid was even more likely to make a particularly close passage of the Earth on August 7, 2027. The minimum possible approach was just 37,000 km from the Earth's center (just 19,000 miles above the surface), but, as with 1997 XF_{11}, the asteroid could just as easily pass outside the Moon's orbit. Figure 5 shows the uncertainty in the predicted close approach in 2027, based on the 123-day data arc available in mid-May, 1999. As before, the uncertainty ellipse is so extremely elongated that it appears as just as a line segment. The center of the ellipse is indicated by the plus sign, located at a nominal distance of 58,000 km from the center of the Earth. The position of the keyhole which led to the possible impact in 2039 is shown at the left end of the uncertainty ellipse. This impacting scenario was still possible, and in fact had become about 100 times more likely, since the new uncertainty ellipse had shrunk by a factor of about 100 from its original size in March.

With the new orbit still indicating a deep encounter in 2027, it could be expected that many more keyholes might exist in the uncertainty region for 1999 AN_{10}. Milani's group in Italy and one of us (PWC) at JPL simultaneously performed new non-linear analyses of the close approach uncertainties, and identified two new impacting possibilities for the years 2044 and 2046. Each required passage through only a single keyhole in the 2027 uncertainty region, and the probabilities of impact for these cases were correspondingly larger than that for 2039. The estimated impact probability for the year 2044 was on the order of 1 in 500,000, and for the year 2046, about 1 in five million. These odds of collision were larger than those for any other object, but they were still less than one hundredth the chance of an undiscovered asteroid of equivalent size striking the Earth sometime before 2044.

As additional observations became available in late May and June, the orbit was refined yet again. The uncertainty region shrank somewhat, and moved completely off the 2039 keyhole, which indicated that this impacting scenario was no longer possible. Then, in July, two German amateurs looking through digitized plate catalogs found pre-discovery images of 1999 AN_{10} on archival plates taken in 1955 for the Palomar Sky Survey. Just as was the case for 1997 XF_{11}, the pre-discovery data enabled the calculation of a greatly improved orbit, and the uncertainties shrank dramatically. Fortunately, the new uncertainty regions did not enclose the keyholes which could lead to impact, and probability of impact for 1999 AN_{10} also shrank, to essentially zero.

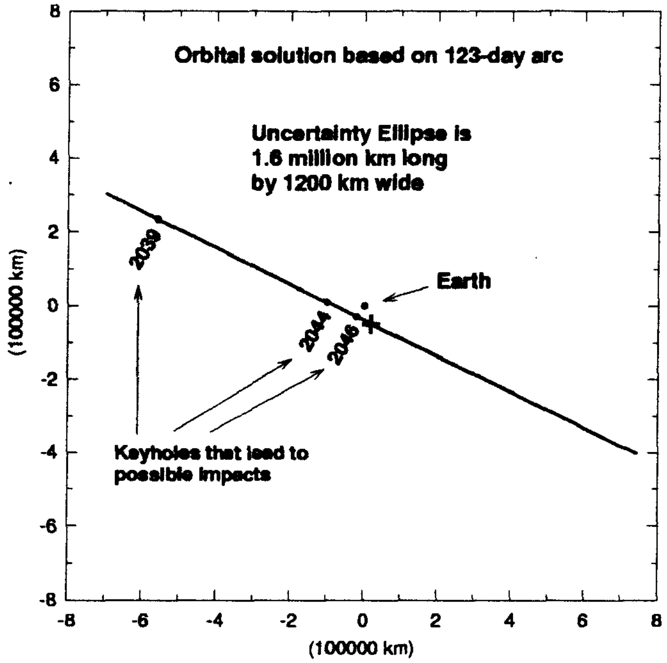

Figure 5 Uncertainty Ellipse for 1999 AN_{10} in 2027 Impact Plane

SUMMARY

In direct contrast to the events that took place for the predicted Earth close approach of asteroid 1997 XF_{11}, the process that took place for the close Earth approaches of 1999 AN_{10} was similar to what should routinely take place in the future when close Earth approaches are predicted. The initial computation were checked and verified by those knowledgeable in these complex computations, the Earth impact probability results were updated as new astrometric data became available, and no premature news accounts were released. Prompted by the issues arising from the future Earth close approaches of asteroids 1997 XF_{11} and 1999 AN_{10} as well as the actual collision of comet Shoemaker-Levy 9 with Jupiter in July 1994, NASA's Near-Earth Object Office has developed the extremely sophisticated tools necessary to accurately characterize future close Earth approaches by, as yet, undiscovered comets and asteroids.

ACKNOWLEDGMENT

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