Near Earth Objects: A Brief Review and A Student Project

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Abstract

We provide a general overview of asteroids which pass close to the Earth: Near Earth Objects (NEOs). NEOs provide information on the formation of the solar system, and may have played an important role in the history of life on Earth. They are easy targets for future space missions. We also describe how to measure the distance to an NEO: an observational exercise for undergraduates which is pedagogically rich, exciting, and requires only modest equipment. We use our own recent data to compute the distances to two objects: 2002 NY40 and 2002 HK12.

I. INTRODUCTION

One of the major challenges facing physics and astronomy instructors is making our subject accessible and exciting to students. While many students seem to know that technology is important in their lives, they have trouble seeing the relevance of basic scientific research. Most students certainly do not expect to make an important scientific contribution as undergraduates.

The study of Near Earth Objects (NEOs) – bodies which pass close to the Earth at some point in their orbit – offers students an opportunity to acquire data which they find meaningful, and which is also needed by the scientific community. In the past several years, the general population has become aware of the threat posed by NEOs. The media has seized upon initial reports of asteroids that may (in the future) threaten the Earth. For example, the Los Angeles Times wrote about the likelihood that asteroid 1950 DA would strike Earth in the year 2880,[1,2] and the New York Times published an article suggesting that asteroid 2002 NT7 had a high probability of striking Earth in 2019[3] (subsequent observations revealed that it would miss Earth by a comfortable margin[4].) During the year 2002, at least 13 asteroids passed within 4 Lunar Orbital Radii (LOR) of the Earth. We list several recent close approaches in Table I and point interested readers to JPL's NEO web site[5].

NEOs are a hot topic at the highest levels of government. At a recent hearing before a panel on space and aeronautics in the House of Representatives, Brigadier General Simon Worden, deputy director for operations of US Strategic Command, pointed out that only the United States has technology sophisticated enough to differentiate asteroids striking the upper atmosphere from nuclear explosions. This was demonstrated on June 6, 2002, when American early-warning satellites detected a flash of energy over the Mediterranean; it turned out to be a 10-meter asteroid hitting the atmosphere, but could easily have been mistaken for a nuclear weapon. To undergraduates who were in high school when *Deep Impact*[6] and *Armageddon*[7] were playing in theaters, this recent press coverage makes NEOs significant and stimulating.

In truth, the chance of the Earth being struck by an asteroid capable of mass extinction in any of our lifetimes is very low (see Table II[8]). Nonetheless, many people find NEOs tantalizing for additional reasons. First, they contain important clues about conditions in the protosolar nebula. Second, they have on occasion been critical to the history of life on

Earth and will probably continue to affect the biosphere well into the future. Third, NEOs may play an important role in future space exploration.

In the next three sections, we will briefly review these aspects of NEOs. In sections V and VI, we describe in detail how one may calculate the distance to an asteroid using simultaneous observations from two locations on the Earth. In section VII, we show our own measurements of two objects, 2002 NY40 and 2002 HK12. We conclude in section VIII.

II. THE EARLY SOLAR SYSTEM

NEOs provide important clues about the early solar system. In the general solar nebula theory, a spinning disk of gaseous material gravitationally collapsed until the central pressures and temperatures reached the point at which fusion began in the proto-Sun. Some of the gas in the disk condensed into liquids or solids depending on its composition and distance from the proto-Sun. Elements with high condensation temperatures, such as tungsten, condensed in the high-temperature environment near the proto-Sun. Organic molecules and ices condensed only in cool regions far from the center, beyond the orbit of Jupiter. The asteroid belt between Mars and Jupiter straddles a dividing line, with the interior dominated by iron- and silicate-rich asteroids, and the more distant orbits filled by bodies composed primarily of lighter elements. In short, some of the ingredients essential to life, such as water and carbon-based organic molecules, condensed only in the outer solar system, while the inner planets were mainly barren rock and metal. It follows that bombardment by asteroids and comets from the outer reaches of the solar system was a likely source of materials essential for life on Earth.[9,10,11,15]

Asteroids and comets can tell us much about the early stages of the solar system. Collisions of the condensed grains of material within the disk built up planetesimals. As these bodies grew, their increasing gravitational pull accelerated the process, which eventually formed the planets. Radioactive decay and collisions heated the planets' interiors, leading to the differentiation of cores and mantles and started large-scale geologic processes. Most asteroids and comets, on the other hand, were far too small for radioactive decay to cause large-scale melting. Their rocky, metallic or icy bodies have remained nearly pristine since they formed. Therefore, small bodies in the solar system have much to tell us about conditions during the accretion phase of the solar system.[16]

Meteorites, of course, are small bodies which have recently fallen onto Earth. The most common and most primitive class of meteorites are the chondrites, which are composed mainly of chondrules. Chondrules are millimeter-sized spheres rich in silicate and metals which were formed as molten droplets, flash heated, and then rapidly cooled. The exact mechanism behind their formation is currently still a hot topic of debate, with candidates ranging from shock waves to massive lightning discharges to bipolar jets or "X-winds". Studies of chondrites provide evidence of temperature gradients within the solar nebula and indicate that the inner solar nebula was completely vaporized.[9,17]

III. BOMBARDMENT AND MASS EXTINCTIONS

Extraterrestrial bombardment has played a major role in the history of life on Earth:

1. there is ample evidence that asteroid and/or comet bombardment brought water to fill Earth's vast oceans;[9,10]
2. further bombardment by asteroids introduced some organic material to our planet;[11]
3. impacts may have caused several mass extinctions over the course of the last several hundred million years;[12]
4. if no other catastrophe destroys humanity first, an impact will likely wipe out our species (and many others) unless we develop a way to defend ourselves against these extraterrestrial marauders.[13,14]

There is strong geological evidence from craters and rare mineral concentrations in the Earth's crust that over the last several hundred million years, tens of asteroids large enough to cause extensive damage have slammed into the Earth.[18] The most notable of impacts was the one that occurred at the Cretaceous-Tertiary (K-T) Boundary approximately 65 million years ago. An asteroid with a diameter of roughly 10 kilometers struck the Yucatan peninsula, creating the Chicxulub crater, estimates of which range from 180 to 300 kilometers in diameter. The global catastrophe obliterated 70 percent of the animal species of the time, including all non-avian dinosaurs.[12,19] It is possible that impacts may have contributed to other mass extinctions as well.[18]

A far less destructive example of bombardment is the Tunguska event, caused by the collision of a (probably) stony asteroid with the atmosphere above a remote region in Siberia. Estimates of the power of this impact range from 15 to 48 Megatons of TNT, roughly 1000 times more destructive than the Hiroshima blast and sufficient to level 2000 square kilometers of forest.[20] While this explosive force may seem insignificant compared to that of the K-T impact, it is notable because it occurred only about a century ago (in 1908). Had it hit a populated area such as New York, Moscow, Paris, or Beijing, instead of a deserted forest, it could have killed large numbers of people. Clearly, extraterrestrial impacts represent a serious danger to the long-term survival of life on Earth.

After passing within the Roche limit of Jupiter on a close approach in 1992, Comet Shoemaker-Levy 9 broke up into 21 separate pieces. In 1994, when our current undergraduates were in junior high or elementary school, the string of comet fragments struck our Jovian neighbor with the equivalent of a billion megatons of TNT.[21] It left scars in the Jovian atmosphere with diameters larger than the Earth. This well-publicized collision raised public awareness of the threat NEOs pose and the need for defense plans (see Appendix).

Some of the credit for the important role asteroids have played in the history of life on Earth should be given to the planet Jupiter. Its tremendous mass prevented a planet from forming in what is now the asteroid belt. Thus, Jupiter is responsible for the existence of many asteroids.[22] Similarly, its mass perturbed the orbits of some of those asteroids,[23] sending them hurtling into the inner solar system to deposit their carbon and water on the inner planets. Its large gravitational attraction for comets and asteroids has also served as a shield, absorbing many of the worst hits from comets (witness Shoemaker-Levy 9). While the presence of Jupiter may have made life possible on Earth, it also threatens it. A main-belt asteroid perturbed by Jupiter into the inner solar system to become a future NEO would pose a fantastic risk to life on our fragile planet.

IV. SPACE EXPLORATION

NEOs may be an important part of future space exploration. On 25 May 1961, President Kennedy challenged the United States to send a man to the moon and return him safely to Earth within a decade, a goal that was completed even earlier than promised. It was a significant milestone in human history. However, there has not been a single crewed flight outside low earth orbit since Apollo 17 returned safely in 1972. In a single decade, we were able to progress from Earth's atmosphere to the lunar surface, but we have not set foot on another heavenly body in the three subsequent decades. Mars may be the next major goal, but before we can safely send a person there, we need to precede it with test missions (as Apollo 7, 8, 9 and 10 were to Apollo 11). A crewed mission to an NEO would seem a logical step on the way to Mars. The right NEO would be a good proving ground for long-duration human space flight beyond Earth orbit, because it would be energetically easier to reach than the Moon,[24] yet take less time than the eight months required to each Mars via Hohmann orbit. The first steps have already taken place: in 2001, the Near Earth Asteroid Rendezvous (NEAR) spacecraft landed on 433 Eros. It was designed only to orbit the asteroid and collect data, but once that mission was complete, NEAR's controllers decided to attempt a landing.[25] They succeeded. Images with a resolution of 30 cm per pixel were recorded, yielding a previously unattained level of detail in our study of NEOs.[26]

In the future, asteroids will retain their allure. They may serve as stepping-stones to deep-space exploration and could be a source of raw materials for construction projects in space. Currently, the cost of boosting anything into orbit is prohibitive: thousands of dollars per pound. Therefore, any type of large interplanetary exploration craft would probably be cheaper to assemble in outer space than on Earth. NEOs could provide the raw materials.[27,28,29] While mining the asteroids remains in the distant future, it is an exciting possibility that our students' children may live to see.

V. MEASURING THE DISTANCE TO AN ASTEROID

We now turn to an experiment involving NEOs which is within the reach of observatories with small budgets: measuring the distance to an asteroid. It requires simultaneous images of the same body from two widely separated sites. Since parallax measurements were last addressed in this journal,[30] they have become much easier due to advances in detector technology, widely available software packages, and the dissemination of minor planet data through the World Wide Web.

Parallax is the apparent shift in the position of a target, relative to more distant objects in the background, when it is observed from two vantage points. An ideal case is shown in Figure 1. If one knows the separation of the observation sites – the baseline B – and measures the angular shift γ, one can use simple trigonometry to calculate the distance d of the target. The calculations are a bit more complex in real situations, when the target is not centered on the baseline, and the baseline is not perpendicular to the line of sight. We show how to handle the general case in section VI.

The most common application of parallax is to measure the distance to a star other than our Sun. The distances between stars are so vast that one needs an enormous baseline to detect any shift at all, even for the Sun's closest neighbors. Therefore, the usual method involves making one observation, waiting six months for the Earth to move to the other side of the Sun (a baseline of roughly 300 million kilometers), and then making a second measurement. In this case, it is customary to quote *half* the angular shift, $\gamma/2$, as the "parallax" of the target.

If one chooses an NEO as the target, however, the distances involved are orders of magnitude smaller, and the baselines required to detect the angular shift become smaller as well. For asteroids which pass within several tens of millions of kilometers of the Earth, baselines within a single continent suffice to show a significant shift. In this situation, one simply makes measurements of the asteroid's position from two widely separated sites on Earth. The two measurements must be simultaneous because the relative orbital motions of the Earth and the NEO cause significant shifts in the target's position in less than a minute. We will use the term "parallax angle" to refer to the entire angle γ by which the target appears to move as seen from the two ends of the baseline.

How can one pick a good target for this experiment? There are several constraints:

1. it must be bright enough for both observatories to detect;
2. it must be moving at an acceptable angular rate through the sky: if angular speed times exposure length is too long, the asteroid will appear as a long streak;
3. it must be close enough that, given the baseline distance between observation sites, it will have a parallax angle a few times larger than the resolution of each telescope.

Most asteroids circle the Sun in a "Main Belt" which lies roughly between the orbits of Mars and Jupiter. They are so far from Earth that only cross-country baselines produce parallax angles far above the threshold of detection. For example, the asteroid 4 Vesta comes within about $d = 2 \times 10^{11}$ meters of the Earth; observatories at opposite ends of the continental

United States would find an angle of 5.3 arcseconds. Since our sites are separated by only a few hundred kilometers, Vesta displays to us a parallax of only 0.5 arcseconds, much too small to measure reliably. We are forced to consider targets which come much closer.

Recent surveys for NEOs, such as LINEAR,[31] have found hundreds of objects in orbits which occasionally bring them much closer to the Earth. One can use several sites on the World Wide Web[4,32] to select asteroids which satisfy all these criteria at any particular time. It is likely that the closest approaches will belong to objects which have been discovered only a week or two earlier. Thanks to these surveys and Internet resources, finding good targets is a much easier task than it was even a decade ago[30].

After performing the experiment several times with different asteroids, we have settled on a few rules which improve the chances for success:

1. Synchronize the clocks at both observatories at the start of each night. We use the time service of the US Naval Observatory[33] as a common standard.
2. Prepare in advance the starting times of a sequence of images with identical mid-exposure times, adding a "hold time" of several minutes between each exposure to allow for focusing and other minor adjustments.
3. Point the telescope at a fixed position so that the asteroid moves across the field during the sequence, rather than slewing the telescope to place the asteroid at the center of each image.
4. Maintain telephone contact during the observing run.
5. Use the same set of reference stars for all reductions (from both sites), if possible.

VI. PARALLAX: DETAILS

We provide below the details of two aspects of the parallax calculations. First, we work through the geometry of the parallax calculation for the general case in which the line of sight to the target and the baseline have arbitrary orientations. Second, we describe briefly how one measures the astronomical coordinates of an asteroid from its position relative to catalogued stars, and then determines the angular shift from the difference in the positions measured at two sites. Our goal is to give novice observers enough information that they may reduce their own data in a manner accurate enough to reveal what we consider a typical parallax: a shift of ten to thirty arcseconds, measured on images taken with small telescopes and relatively inexpensive CCDs. Readers who do not plan to perform the experiment themselves may skip this section. Those who need more information on these topics should consult texts on spherical trigonometry and astrometry.[34,35]

The basic procedure for calculating the parallax distance to a given NEO is to

1. determine the effective baseline distance between the two observing sites;
2. measure the parallax angle from the data;
3. apply basic trigonometry to determine the distance to the target object at the time of the observations.

First, we must define the positions of observatories X and Y in three-dimensional space based upon their latitude ϕ, longitude l, and the radius of the Earth $R_E = 6378.2$ km. We choose a spherical coordinate system with one angle set by the Earth's rotational axis, and the other angle defined by the longitude of observatory X. Setting the difference in longitudes to be $\beta \equiv l_X - l_Y$, we may express the locations of the observatories as

$$\vec{X} = [R_E \cos(\phi_X), 0, R_E \sin(\phi_X)] \tag{1}$$

and

$$\vec{Y} = [R_E \cos(\phi_Y) \cos(\beta), R_E \cos(\phi_Y) \sin(\beta), R_E \sin(\phi_Y)]. \tag{2}$$

This coordinate system moves with the Earth, following the wobble of the Earth's axis due to precession and nutation. The positions of stars and asteroids in the sky, on the other hand, are described by an inertial reference system: in our case, the J2000.0 system adopted by the USNO A2.0 stellar catalog. These two coordinate systems agree only at one specific time (0 hours UT on Jan 1, 2000). Strictly speaking, one should correct the catalog positions to the time of each observation before reducing the data. In the case of 2002 NY40, observed 2.6 years after the equinox of the catalog, precession shifts the catalog positions by about 123 arcseconds, and nutation by about 3 arcseconds. However, because our experiment is a doubly differential one – we measure an asteroid's position relative to stars in each frame, and then look for a shift between those two positions – the effect of an offset in coordinate systems is very small. In the case of 2002 NY40, the corrections introduce a change of approximately 0.004 arcseconds in the parallax angle. By comparison, the dominant sources of error – finding the centroid of the slightly trailed asteroid image, and transforming the instrumental positions of stars to the reference catalog positions – are between 0.5 and 1.0 arcseconds each. Observers like us, using telescopes less than a meter in diameter at sites with mediocre seeing, may safely ignore the consequences of using two different coordinate systems.

As shown in Fig. 2, the chord distance $\vec{C}$ between the two sites is the difference $\vec{X} - \vec{Y}$ between the two positions

$$\vec{C} = R_E[\cos(\phi_X) - \cos(\phi_Y)\cos(\beta), -\cos(\phi_Y)\sin(\beta), \sin(\phi_X) - \sin(\phi_Y)]. \tag{3}$$

We now define a unit vector from observatory X to the asteroid, which we call $\hat{W}$ and write as

$$\hat{W} = [\cos(H)\cos(\delta), \sin(H)\cos(\delta), \sin(\delta)], \tag{4}$$

where δ is the declination of the asteroid and H is the hour angle of the asteroid as seen from site X. The baseline $\vec{B}$ is that portion of $\vec{C}$ which is perpendicular to $\hat{W}$. The vectors $\hat{W}$ and $\vec{C}$ are separated by an angle θ; see Fig. 3, which shows that

$$|\vec{B}| = |\vec{C}|\sin(\theta). \tag{5}$$

The angle θ between $\hat{W}$ and C can be determined from the dot product

$$\cos(\theta) = \frac{\vec{C}\cdot\hat{W}}{|\vec{C}||\hat{W}|} = \frac{\vec{C}\cdot\hat{W}}{|\vec{C}|}. \tag{6}$$

Now we know the length of the baseline $\vec{B}$. The second step, calculating the parallax angle γ from the images taken at the two sites, involves some astrometry which we defer for a moment. Finally, given $\vec{B}$ and γ, we can determine the distance d to the asteroid. As shown in Fig. 1,

$$\tan(\gamma/2) = \frac{B/2}{d}. \tag{7}$$

Rearranging to solve for d, and substituting from Eq. (5), we have

$$d = \frac{C\sin(\theta)}{2\tan(\gamma/2)}. \tag{8}$$

The only remaining task is to measure the parallax angle γ from simultaneous images of the asteroid. Identifying the asteroid is easy: one may either examine a sequence of images to find the moving object, or compare a single image to a reference image from one of the many available surveys (using, for example, the SkyView[36] tool). Calculating its position is not trivial because our flat two-dimensional images do not reflect perfectly the three-dimensional nature of the real sky. Fortunately, given the small field of view (less than one degree) of typical images taken with telescopes of moderate size, the distortions are not difficult to model.

Astronomers describe the positions of stars on the sky the same way geographers describe the positions of cities on the globe: with a curvilinear two-dimensional coordinate system. "Right Ascension" (α) is the equivalent of longitude, and "Declination" (δ) takes the place of latitude. There are several catalogs containing the (α, δ) positions of stars similar to NEOs in brightness, such as the USNO-SA2.0[37] and USNO-B1.0[38] If we can identify these stars in our images, we can use them to determine the transformation between (α, δ) on the sky and pixel coordinates (x, y) in our images. The procedure consists of several steps for each image:

1. measure (x, y) positions of stars and target;
2. match stars in image with stars in catalog;
3. project the (α, δ) coordinates of stars onto a tangent plane, yielding "standard coordinates" (ξ, η) (see Chapter 12 of Smart[35] or Section 3.2 of Olkin *et al.*[39]);
4. find a transformation which takes the (x, y) values for stars in the image to their (ξ, η) values (a simple linear model often suffices);
5. transform the (x_0, y_0) position of the target to its (ξ_0, η_0) equivalent;
6. de-project the target's (ξ_0, η_0) to the (α, δ) coordinate system.

This is a tedious task, as one of us (MWR) can attest after doing it repeatedly for this project. Fortunately, there are a number of inexpensive software packages available now which automate the entire process. We tested several software packages including Astroart,[40] Astrometrica,[41] Computer-Aided Astrometry,[42] and FITSblink.[43] We have found that Astroart suits our purposes the best. It can be used with a variety of star catalogs and, with a little experience, is quite quick and easy to use. We compared the results of Astroart to those of our own calculations[44] and found good agreement as long as there were at least fifteen reference stars in the image.

Once one has found the (α, δ) positions of the asteroid in simultaneous images from two sites, the parallax γ is simply their angular difference. Strictly speaking, one must compute

$$\cos(\gamma) = \cos(90^\circ - \delta_X)\cos(90^\circ - \delta_Y) + \sin(90^\circ - \delta_X)\sin(90^\circ - \delta_Y)\cos(\alpha_X - \alpha_Y). \tag{9}$$

However, because this angular shift is in practice very small, one may use the easily remembered "Pythagorean" approximation

$$\gamma \simeq \sqrt{((\alpha_X - \alpha_Y)\cos(\delta_X))^2 + (\delta_X - {\delta_Y}^2)}. \tag{10}$$

VII. OBSERVATIONS AND ANALYSIS

We have made simultaneous observations of several NEOs from our observatories at the United States Naval Academy (USNA) and the Rochester Institute of Technology (RIT). The USNA Observatory is on top of Michaelson Hall, a four-story building on the bank of the Severn River. We use a 20-inch DFM Schmidt-Cassegrain telescope with a Roper Scientific CE300 series CCD camera. This combination yields a field of view of 15 × 15 arcminutes and a plate scale of 0.886 arcseconds per pixel. We use a red filter ($\lambda > 5900$ Å) to reduce artificial light. The RIT Observatory sits in an empty corner of the RIT campus, about six miles from downtown Rochester. We use a 10-inch Meade LX-200 telescope and SBIG ST-8E CCD camera for our asteroid work; with an f/6.3 focal reducer, our field of view is about 17 by 24 arcminutes, and our scale about 1.9 arcsecond per pixel. We acquire images without a filter in order to gain enough photons in a short exposure to determine the position of each object accurately.

In the mathematical expressions below, we designate RIT as site X and USNA as site Y. The latitudes of RIT and USNA are $l_X = +43\overset{\circ}{.}0758$ and $l_Y = +38\overset{\circ}{.}9838$ respectively, and the difference in longitude is $\beta = 1\overset{\circ}{.}18$. The vector $\vec{C}$, the chord between Rochester and Annapolis, is $(298, 102, -343)$ km, with a magnitude of 466 km.

We observed asteroid 2002 NY40 on the night of August 17, 2002, at approximately midnight local or 04:00 Universal Time (UT). There were clouds at both sites, which obscured the fainter reference stars in some of images, especially those taken later in the run. We started images at the top of each minute and exposed them for 10 seconds. The vector $\vec{W}$, the direction to the asteroid, changed by about two percent during the run. We calculated the baseline at the time of each pair of images; the average value was about $B = 377$ km. Figures 4 and 5 show a portion of the images taken at UT 04:22 from each site; one can see clearly the shift in the asteroid's position. We show our measurements of the asteroid's position from both sites in Table III, the corresponding parallax angles in Table IV, and the computed distances in Table V. Our distances are within several percent of the true value (taken from the JPL Ephemeris[45]); the errors are largest in the final image, which suffered most from clouds.

We observed a second NEO, asteroid 2002 HK12, several weeks later, acquiring images between 04:30 UT and 05:00 UT on September 7, 2002. Because this asteroid was much closer to the Earth than 2002 NY40 (only one-fifth the distance), its apparent motion was much faster. Because 2002 HK12 was relatively faint, we had to expose our images for 20 seconds; as a result, the asteroid left a slight trail, which marginally increased the uncertainty in its position. As the direction vector $\hat{W}$ shifted, our baseline changed from $B = 367$ km at 04:40 UT to $B = 382$ km just twenty minutes later. We present our positions of the asteroid in Table VI, the corresponding parallax angles in Table VII, and the distances to the asteroid in Table VIII. Once again, we compare our distance to that derived from the JPL Ephemeris.[45] The improvement in our measurements during the run is due to the increasing altitude of the asteroid above the horizon, which affects our measurements in three ways: light from the asteroid suffers less extinction, providing a larger signal; the image is sharper, allowing us to calculate its centroid more precisely; and less stray light from nearby streetlamps and other human sources enters the telescope aperture.

After reducing our data, we sent our measurements of the position and brightness of each asteroid to the Minor Planet Center (MPC). In addition to acting as a clearinghouse for information on bodies in the solar system, the MPC provides information and references on astrometry of asteroids for the beginner. We urge interested parties to study their materials[46] before starting an observing project. Because NEOs are typically observed for only a few weeks around a single close approach to Earth, their orbits are not as well defined as those of main-belt asteroids. Our measurements can help astronomers at the MPC to improve the orbital elements for these objects, especially if bad weather hampers other observatories during a crucial period.

VIII. CONCLUSIONS

Both we and our students find asteroids which zip past the Earth interesting and exciting. Even those with modest instruments can make important contributions to the study of NEOs. Our students are particularly excited that their own measurements may significantly improve our ability to predict future close encounters. We have shown that coordinated observations from sites in different states can yield the distances to NEOs with an accuracy of several percent, and describe the analysis in detail so that others may use it as a guide for their own experiments. Those interested in following our example may find partners for parallax experiments by going to the Collaborative Asteroid Lightcurve Link[47] and posting an announcement.

NEOs have been critical in the history of life on Earth and they may provide a means for us to voyage out into the stars. Earth started as humankind's home and will likely remain so for eons to come, but if we are to ensure the survival of our species for the ages, we must make plans to defend the Earth from NEOs and find a way to live beyond this fragile ball hanging in space. NEOs may have given us life and indirectly helped to bring us to our current position of dominance on the planet, but if we are not vigilant, they may one day rob us of our privileged position.

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[1] McFarling, Usha Lee, "Asteroid Offers a Plot Made for Hollywood," Los Angeles Times, April 8, 2002, Part 1, page 5

[2] Giorgini, J. D. et al. 2002, “Asteroid 1950 DA’s Encounter with Earth in 2880: Physical Limits of Collision Probability Prediction”, Science, 296, 132-136

[3] Chang, Kenneth, “New Asteroid has Long Odds for Earth Crash,” New York Times, July 25, 2002, Section A, page 10

[4] `http://cfa-www.harvard.edu/iau/lists/CloseApp.html`

[5] `http://neo.jpl.nasa.gov/neo/close.html`

[6] *Deep Impact*, film produced by DreamWorks SGK/Paramount Pictures, Los Angeles, 1998

[7] *Armageddon*, film produced by Jerry Bruckheimer Films/Touchstone Pictures, Los Angeles, 1998

[8] Morrison, D., Chapman, C. R., & Slovic, P. 1994, “The Impact Hazard”, Hazards Due to Comets and Asteroids, 59

[9] Alexander, C. M. O., Boss, A. P., & Carlson, R. W. 2001, “The Early Evolution of the Inner Solar System: A Meteoritic Perspective”, Science, 293, 64

[10] Ozernoy, L. M. & Ipatov, S. I. 2001, “Origins of Water on Mars, Earth, and Venus: Evaluating the Supply from the Outer Solar System”, American Astronomical Society Meeting 199, #28.06

[11] Kouchi, A., Kudo, T., Nakano, H., Arakawa, M., Watanabe, N., Sirono, S., Higa, M., & Maeno, N. 2002, “Rapid Growth of Asteroids Owing to Very Sticky Interstellar Organic Grains”, Astrophysical Journal Letters, 566, L121-L124

[12] Alvarez, L. W., Alvarez, W., Asaro, F., & Michel, H. V. 1980, “Extraterrestrial Cause for the Cretaceous Tertiary Extinction”, Science 208, 1095

[13] Lupishko, D. F. 2000, “Physical Properties of Near-Earth Asteroids as Principal Impactors Onto the Earth”, Catastrophic Events and Mass Extinctions: Impacts and Beyond, p. 118

[14] Morbidelli, A., Bottke, W. F., Jedicke, R., Michel, P., & Tedesco, E. F. 2001, “NEO Albedo Distribution and Impact Hazards”, American Astronomical Society, DPS meeting #33, #54.06

[15] Lunine, J. I., Owen, T. C., & Brown, R. H. 2000, “The Outer Solar System: Chemical Constraints at Low Temperatures on Planet Formation”, Protostars and Planets IV, 1055

[16] Shu, F. H. 2000, “What Do Meteorites Tell Us about the Formation of the Solar System?”, Bulletin of the American Astronomical Society, 197, 201

[17] Jones, R. H., Lee, T., Connolly, H. C., Love, S. G., & Shang, H. 2000, “Formation of Chondrules and CAIs: Theory VS. Observation”, Protostars and Planets IV, 927

[18] Rampino, M. R. & Haggerty, B. M. 1994, “Extraterrestrial Impacts and Mass Extinctions of

Life", Hazards Due to Comets and Asteroids, 827

[19] Smit, J. 1994, "Extinctions at the Cretaceous-Tertiary Boundary: the Link to the Chicxulub Impact", Hazards Due to Comets and Asteroids, 859

[20] Simonenko, V. A., Nogin, V. N., Petrov, D. V., Shubin, O. N., & Solem, J. C. 1994, "Defending the Earth Against Impacts from Large Comets and Asteroids", Hazards Due to Comets and Asteroids, 929

[21] Park, R. L., Garver, L. B., & Dawson, T. 1994, "The Lesson of Grand Forks: Can a Defense against Asteroids be Sustained?", Hazards Due to Comets and Asteroids, 1225

[22] Ruzmaikina, T. V., Safronov, V. S., & Weidenschilling, S. J. 1989, "Radial mixing of material in the asteroidal zone", Asteroids II, 681-700

[23] Dahlgren, M., Hahn, G., Lagerkvist, C.-I., & Lundstroem, M. 1992, "The orbital evolution of real asteroids near the 4:1 mean-motion resonance with Jupiter", Lunar and Planetary Inst., Asteroids, Comets, Meteors, 145-148

[24] Jones, Thomas D., Air & Space, April/May 2002, 62

[25] Asphaug, E. 2001, "Once upon an asteroid", Nature (London) , 413, 369-370

[26] Veverka, J. et al. 2001, "The landing of the NEAR-Shoemaker spacecraft on asteroid 433 Eros", Nature (London) , 413, 390-393

[27] Gertsch, L. S. & Gertsch, R. E. 2000, "Mine Planning for Asteroid Orebodies", Space Resources Roundtable II, 19

[28] Reed, K. L. 2000, "An End-To-End Near-Earth Asteroid Resource Exploitation Plan", Space Resources Roundtable II, 47

[29] Benson, J. 1998, "Near-Earth Asteroid Prospector and the Commercial Development of Space Resources", Workshop on Using In Situ Resources for Construction of Planetary Outposts, 2

[30] Ratcliff, Stephen J. *et al.*, 1993, "The measurement of astronomical parallaxes with CCD imaging cameras on small telescopes", AJP 61, 208-216

[31] Stokes, G. H., Evans, J. B., Viggh, H. E. M., Shelly, F. C., & Pearce, E. C. 2000, "Lincoln Near-Earth Asteroid Program (LINEAR)", Icarus, 148, 21-28

[32] `http://ssd.jpl.nasa.gov/cgi-bin/what_obs`

[33] `http://tycho.usno.navy.mil`

[34] Green, R. M. 1985, *Spherical Astronomy*, (Cambridge and New York: Cambridge University Press)

[35] Smart, W. M. 1977, *Textbook on Spherical Astronomy* (Cambridge: University Press)

[36] `http://skyview.gsfc.nasa.gov/cgi-bin/titlepage.pl`

[37] Monet, D. B. A. et al. 1998, VizieR Online Data Catalog, 1252

[38] Monet, D. G., Levine, S. E., Casian, B., & et al. 2002, “The USNO-A2.0 Catalogue”, VizieR Online Data Catalog, 1284

[39] Olkin, C. B., Elliot, J. L., Bus, S. J., McDonald, S. W., & Dahn, C. C. 1996, “Astrometry of Single-Chord Occultations: Application to the 1993 Triton Event”, Publications of the Astronomical Society of the Pacific, 108, 202

[40] `http://www.msb-astroart.com/`

[41] `http://www.astrometrica.at/`

[42] `http://www.camarilloobservatory.com/caawin.htm`

[43] `http://www.rcp.ijs.si/~jure/fitsblink/fitsblink.html`

[44] `http://spiff.rit.edu/tass/match/match.html`

[45] `http://ssd.jpl.nasa.gov/horizons.html`

[46] `http://cfa-www.harvard.edu/iau/mpc.html`

[47] `http://www.minorplanetobserver.com/astlc/default.htm`

[48] Gold, R. E. 2001, “SHIELD: a comprehensive earth-protection architecture”, Advances in Space Research, 28, 1149-1158

[49] Spitale, J. 2002, “Asteroid hazard mitigation using the Yarkovsky effect”, Science, 296, 5565

[50] Spitale, J. & Greenberg, R. 2002, “Numerical Evaluation of the General Yarkovsky Effect: Effects on Eccentricity and Longitude of Periapse”, Icarus, 156, 211-222

[51] Milani, A. 2001, Tumbling Stone, `http://spaceguard.ias.rm.cnr.it/tumblingstone/issues/special-palermo/article1.htm`

[52] `http://www.jpl.nasa.gov/releases/2002/release_2002_79.html`

[53] Spitale, J. N. 2002, “NEA Hazard Mitigation Using the Yarkovsky Effect”, Lunar and Planetary Institute Conference Abstracts, 33, 1223

APPENDIX A: DEFENSE PLANS

With all the talk of the threat NEOs pose to Earth, most people justifiably want to know what we can actually do if we detect an asteroid on a collision course with Earth. There are several plans, some possible with current technology, others requiring the development of more sophisticated systems. All of them boil down to one of two goals: alter the object's orbit enough that it will not hit Earth, or reduce it to pieces small enough to burn up in Earth's atmosphere. Here we briefly summarize some options. Details can be found in the references.[48,49,50]

Currently, the only option we have is to launch a large number of nuclear warheads at an incoming asteroid or comet. This may also be the only option even in the future for objects that we detect with little advance warning. Nuclear weapons could be detonated at standoff range or soft-landed on the body and then detonated in order to change its orbit. They could also be buried in the NEO before exploding to fragment it. Fragmentation has its own perils, as several smaller but still deadly bodies hurtling at Earth may be no better than a single large impactor.

Another option is to mount engines on the asteroid or comet. Whether these engines are chemical, electrical or even nuclear, the goal is the same: to provide enough thrust to alter the object's orbit so that it misses Earth. The difficulty posed by this scheme is that it not only requires landing on an asteroid, but doing so with sufficient time to change the orbit. Instead of engines, one may use solar sails, designed to harness the momentum of solar radiation, but sails require a complex harness which can keep them at a constant position relative to the Sun as the asteroid rotates.

A kinetic impactor is the simplest idea: accelerate an object to a high velocity and place it on a collision course with the incoming body. However, it is not trivial to give a missile the momentum required to alter an NEO's orbit significantly. In addition, this strategy risks fragmentation.

Could one make use of the Yarkovsky effect? Thermal photons leaving the surface of a body with non-uniform surface temperatures carry momentum, producing a reaction force on the body. Therefore, if the albedo or surface thermal conductivity of a body were changed (by spreading dark or light powder over a portion of its surface, for example), the reaction force might alter its orbit enough to avoid collision with Earth. Unfortunately, this effect provides such a small force that it could take hundreds of years to change the orbit significantly, meaning that the asteroid would have to be detected well in advance. Such an approach would be feasible for asteroids like 1950DA,[51,52,53] which is forecast to have a close approach in 2880.

In the more distant future, advances in technology may give us more options. Some have envisioned comprehensive satellite systems, designed to defend the Earth at every stage of the threat. Dedicated Sentry satellites would be equipped with cameras and enough computing power to detect and track NEOs. They would maintain databases of known orbits and be capable of forecasting the threat posed by an object. Any detected threats would be engaged by a series of Soldier satellites.

Whichever defense we choose, we must prepare; it is not a question of “if” we will be struck again, but rather of “when.”

TABLE I: Some recent close approaches

Date	Asteroid	Distance(LOR)[a]	Diameter (m)[b]
11 Dec 2002	2002 XV90	0.33	
27 Aug 2002	2002 HK12	20	
18 Aug 2002	2002 NY40	1.25	
17 Jul 2002	2002 MN	0.33	50-120
31 Mar 2002	2002 GQ	1.5	
08 Mar 2002	2002 EM7	1.2	50
08 Feb 2002	2002 CB26	1.7	
05 Feb 2002	2002 CA26	3.5	
07 Jan 2002	2001 YB5	3.0	300
01 Dec 1994	1994 XM1	0.33	

[a] LOR = 1 Lunar Orbital Radius = 384,000 km

[b] Few NEOs have accurate size estimates

TABLE II: Destructive potential and frequency of asteroid impact[8]

Size(km)	Equivalent Yield (Mt of TNT)	Typical interval (years)
0.01	0.1	5
0.03	3	1×10^2
0.1	1×10^2	1×10^3
0.3	3×10^3	5×10^4
1	1×10^5	5×10^5
3	5×10^6	1×10^7
10	1×10^8	1×10^8

TABLES

TABLE III: Astrometry (J2000) of 2002 NY40 on 17 Aug 2002

	RIT		USNA	
Time(UT)	α	δ	α	δ
04:22:05	20 57 16.86	+04 47 58.7	20 57 16.22	+04 48 34.6
04:30:05	20 57 04.29	+04 50 49.7	20 57 03.58	+04 51 23.9
04:32:05	20 57 01.02	+04 51 32.6	20 57 00.41	+04 52 06.5
04:38:05	20 56 51.62	+04 53 39.4	20 56 50.81	+04 54 15.7
04:50:05	20 56 32.50	+04 58 00.5	20 56 31.55	+04 58 37.2
04:54:05	20 56 26.14	+04 59 27.3	20 56 24.90	+05 00 03.3

TABLE IV: Parallax angle (arcseconds) of 2002 NY40

Time(UT)	$\Delta\alpha$	$\Delta\delta$	γ
04:22:05	9.6	−35.9	37.2
04:30:05	10.6	−34.2	35.8
04:32:05	9.1	−33.9	35.1
04:38:05	12.1	−36.3	38.3
04:50:05	14.2	−36.7	39.4
04:54:05	18.5	−36.0	40.5

TABLE V: Distance to 2002 NY40

Time(UT)	d(LOR)[a]	d(10^6 km)	JPL d(10^6 km)	Error[b](10^6 km)	Percent error
04:22:05	5.50	2.113	2.122	-0.009	-0.4
04:30:05	5.72	2.198	2.112	+0.086	+4.1
04:32:05	5.84	2.242	2.110	+0.132	+6.3
04:38:05	5.36	2.057	2.103	-0.046	-2.2
04:50:05	5.21	2.002	2.088	-0.086	-4.1
04:54:05	5.08	1.949	2.083	-0.134	-6.4

[a] LOR = 1 Lunar Orbital Radius = 384,000 km

[b] Difference between our distance and that taken from the JPL Ephemeris JPL#50-DASTCOM3

TABLE VI: Astrometry (J2000) of 2002 HK12 on 07 Sep 2002

	RIT		USNA	
Time(UT)	α	δ	α	δ
04:40:10	04 10 19.90	+43 10 11.9	04 10 20.45	+43 10 18.5
04:45:10	04 10 17.13	+43 09 59.8	04 10 17.70	+43 10 06.7
04:50:10	04 10 14.52	+43 09 49.0	04 10 14.95	+43 09 55.3
04:55:10	04 10 11.69	+43 09 37.6	04 10 12.18	+43 09 43.8

TABLE VII: Parallax angle (arcseconds) of 2002 HK12

Time(UT)	$\Delta\alpha$	$\Delta\delta$	γ
04:40:10	-6.0	-6.6	8.9
04:45:10	-6.2	-6.9	9.3
04:50:10	-4.7	-6.3	7.9
04:55:10	-5.4	-6.2	8.2

FIGURE CAPTIONS

TABLE VIII: Distance to 2002 HK12

Time(UT)	d(LOR)[a]	d(10^6km)	JPL d(10^6 km)	Error[b](10^6 km)	Percent error
04:40:10	27	10.3	11.12	-0.84	-7.6
04:45:10	26	9.90	11.13	-1.23	-11
04:50:10	30	11.7	11.13	+0.61	+5.5
04:55:10	29	11.3	11.13	+0.16	+1.5

[a] LOR = 1 Lunar Orbital Radius = 384,000 km

[b] Difference between our distance and that taken from the JPL Ephemeris JPL#77-DASTCOM3

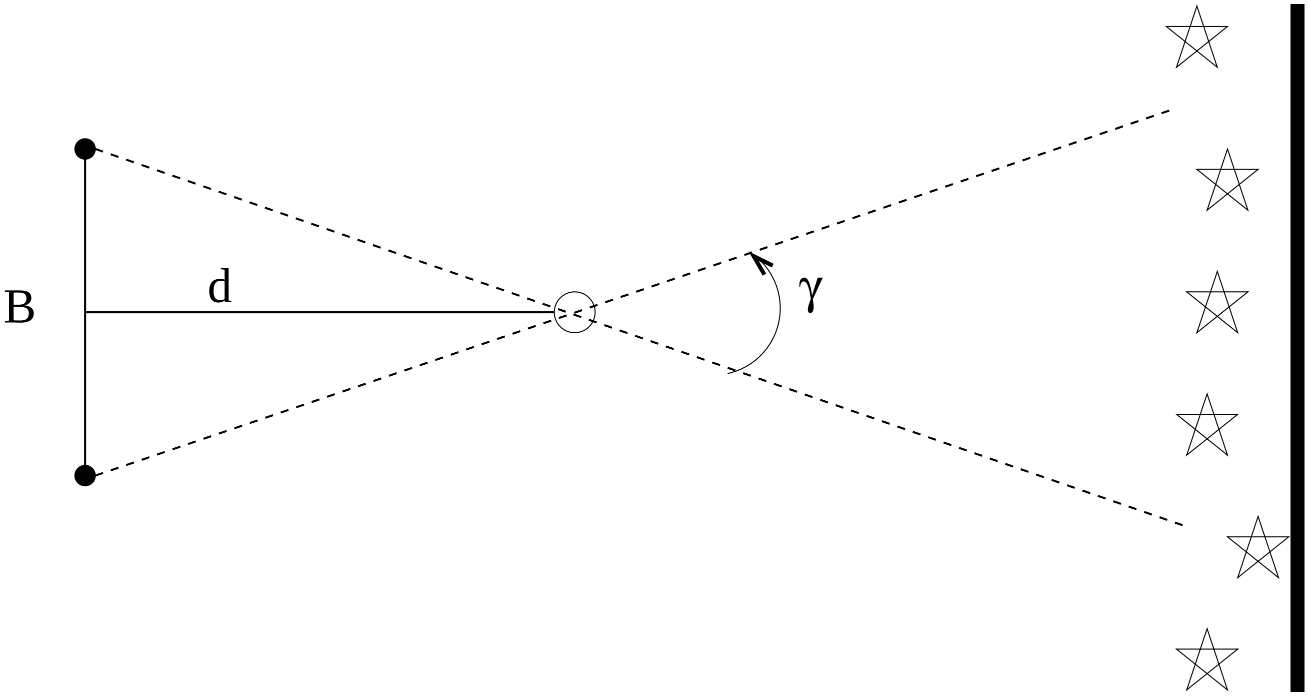

FIG. 1: The parallax angle in an ideal case: observers at the ends of baseline B measure an angular shift γ of an asteroid relative to distant stars. Note that in other contexts, “parallax angle” sometimes refers to half of γ.

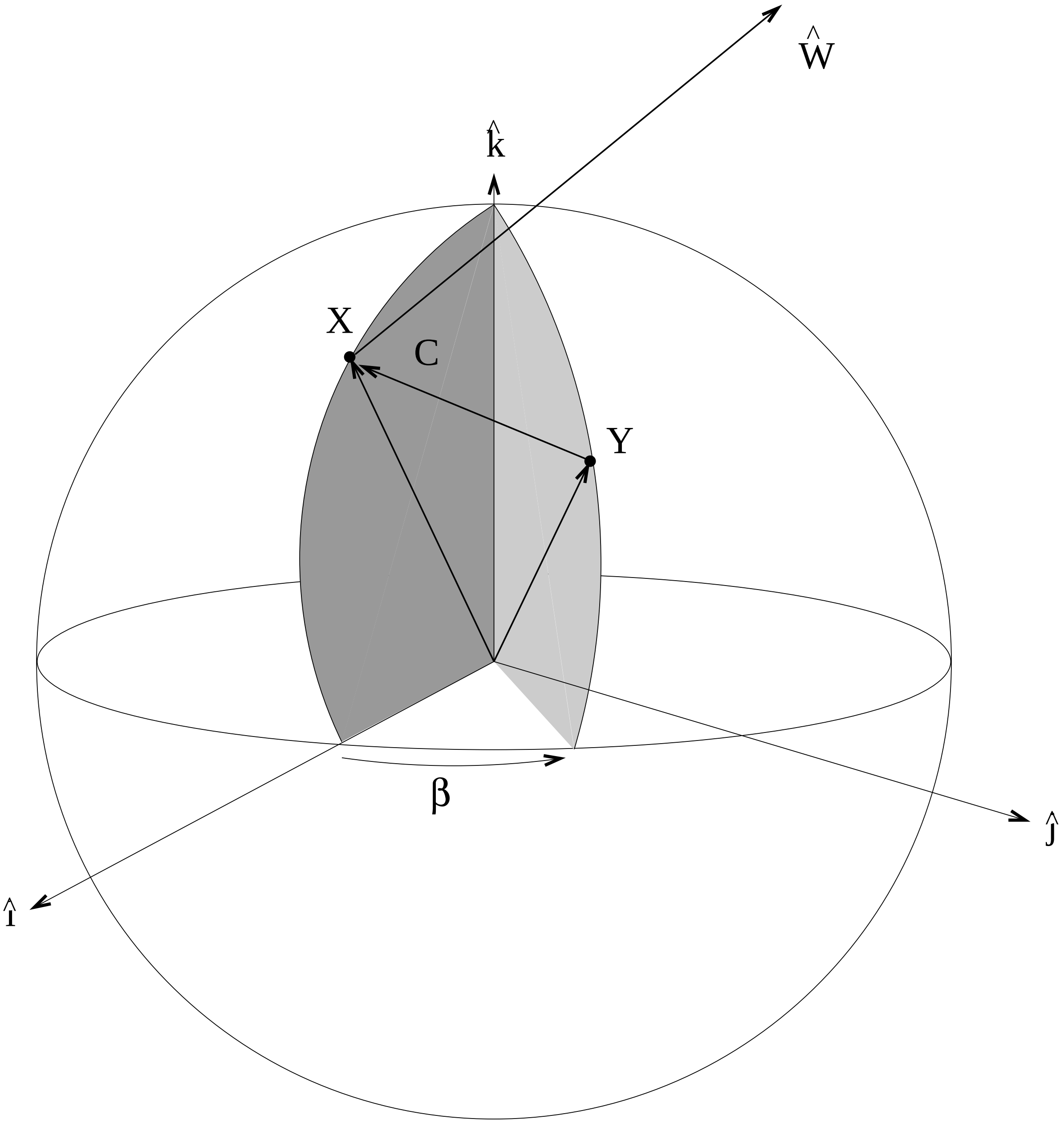

FIG. 2: Definition of the vectors required to determine the baseline. X and Y refer to the two observatories. The unit vector $\hat{W}$ points to the asteroid.

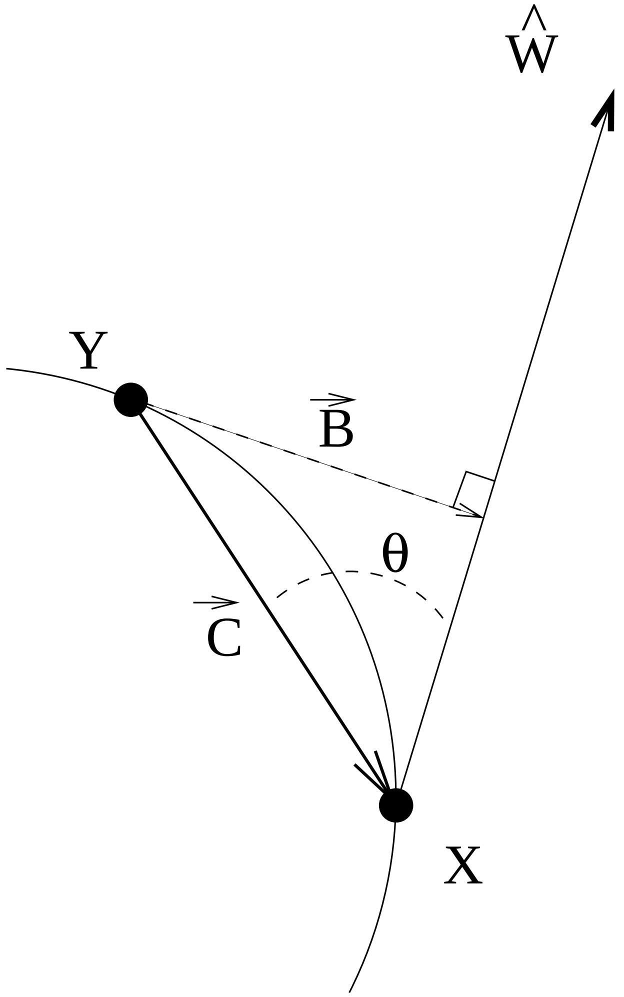

FIG. 3: Detail of Figure 2 from above the North Pole, showing the relationship between chord $\vec{C}$ and the baseline $\vec{B}$.

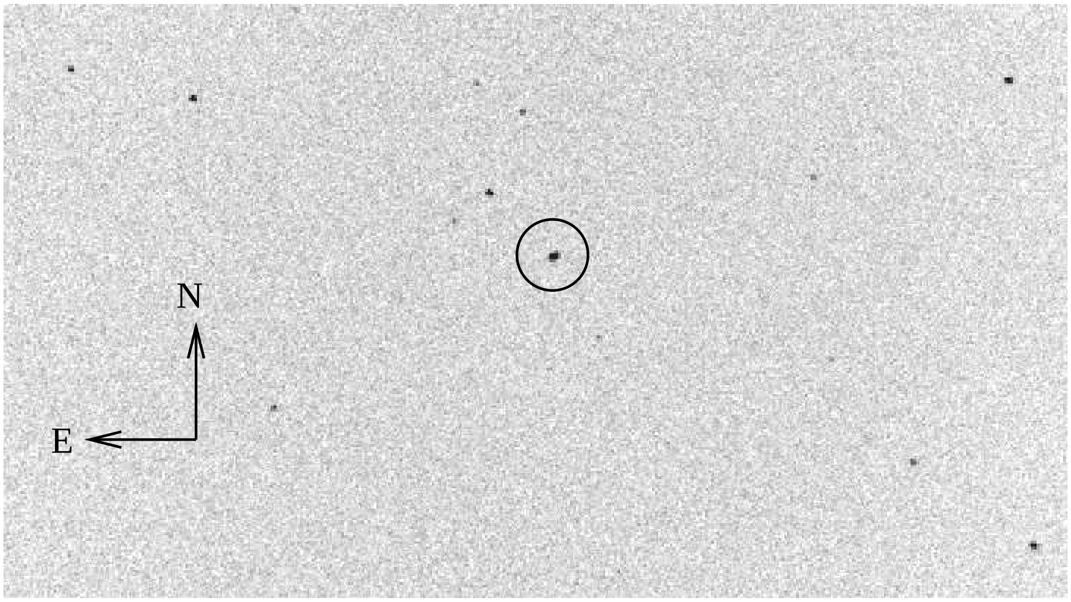

FIG. 4: Central portion of the RIT image of 2002 NY40 taken at UT 2002 Aug 17 04:22. The field is roughly 15 by 10 arcminutes on a side.

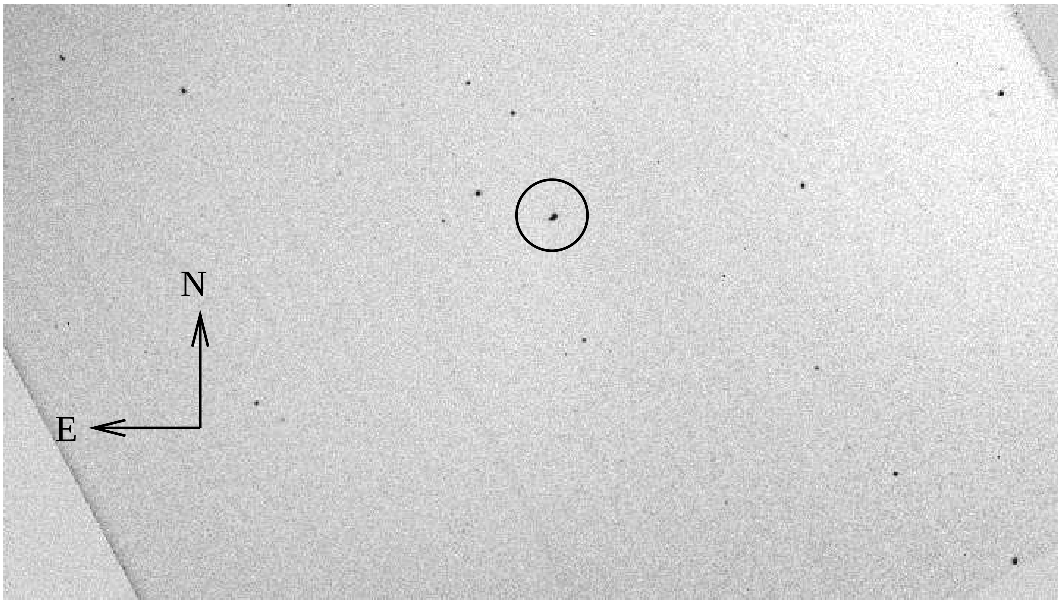

FIG. 5: Central portion of the USNA image of 2002 NY40 taken at UT 2002 Aug 17 04:22. The field is roughly 15 by 10 arcminutes on a side.